Texas Water Resources Institute
Annual Technical Report
FY 2011

Introduction

The Texas Water Resources Institute (TWRI), a unit of Texas AgriLife Research, Texas AgriLife Extension Service and the College of Agriculture and Life Sciences at Texas A&M University, and a member of the National Institutes for Water Resources, provides leadership in working to stimulate priority research and Extension educational programs in water resources. Texas AgriLife Research and the Texas AgriLife Extension Service provide administrative support for TWRI and the Institute is housed on the campus of Texas A&M University.

TWRI thrives on collaborations and partnerships and in fiscal year 2011 managed 40 active projects with $15,691,381 in funds. Those projects involved more than 100 Texas A&M University System faculty members and graduate students as well as faculty from other universities across the state. The Institute maintained joint projects with 16 Texas universities and four out-of-state universities; federal, state and local governmental organizations; consulting engineering firms, commodity groups and environmental organizations; and numerous others. In 2011 the Institute was awarded 9 new TWRI-lead projects with direct funding of $2,317,710.

TWRI works closely with agencies and stakeholders to provide research-derived, science-based information to help answer diverse water questions and also to produce communications to convey critical information and to gain visibility for its cooperative programs. Looking to the future, TWRI now awards a Water Assistantship to graduate students at Texas A&M University through funding provided by the W.G. Mills Endowment and the U.S. Geological Survey.

Research Program Introduction

Through the funds provided by the U.S. Geological Survey, TWRI funded 10 research projects in 2011-12 conducted by graduate students at Texas A&M University (4 projects), West Texas A&M University (1 project), the University of Texas at Austin (1 project), the University of Texas at Arlington (1 project), Texas Tech University (1 project), Sam Houston State University (1 project) and Texas State University (1 project). Additionally, through funds provided by the U.S. Geological Survey, TWRI facilitated the continuation of three competitive research programs at Texas A&M University, another at Texas State University, and a multi-state, international project.

Jacob Becker, of West Texas A&M University, assessed low ear placement corn hybrids as a way of increasing water use efficiency.

Cora Lea Emerson, of Texas Tech University, examined cotton-biofuels production systems in a changing High Plains Environment.

Rebecca Hammond, of Sam Houston State University, researched landscape coefficients in mixed species landscapes.

Chungyeon Cho, of Texas A&M University, studied reusable magnetic janus particle scavengers for environmentally-friendly remediation of contaminated water bodies.

Sarah Keithley, of the University of Texas at Austin, studied the effects of treatment on harvested rainwater quality.

C. Prakash Khedun, of Texas A&M University, assessed water availability in Texas using the NOAH land surface model.

Shae Luther, of Texas State University, examined the benefits and costs of water reuse programs in Texas.

April Mattox, of Texas A&M University, researched the effects of woody vegetation removal on groundwater recharge in the Carrizo-Wilcox aquifer.

Michael Neisch, of Texas A&M University, evaluated grass carp (Ctenopharyngodon idella) as a biocontrol agent for giant salvinia (Salvinia molesta).

Prince Nfodzo, of the University of Texas at Arlington, examined in situ remediation of the Trinity River sediment contaminated with polychlorinated biphenyls.

Dr. Vijay P. Singh, of the department of biological and agricultural engineering at Texas A&M University, continued researching hydrological drought characterization for Texas under climate change, with implications for water resources planning.

Dr. Benjamin F. Schwartz, of the department of biology at Texas State University, continued examining the role of epikarst in controlling recharge, water quality and biodiversity in karst aquifers – comparing Virginia and Texas.

Dr. Ron Griffin, of the Department of Agricultural Economics at Texas A&M University, continued researching institutional mechanisms for accessing irrigation district water.

Finally, the other competitive research grant is a multi-state, international effort that involves the collection and evaluation of new and existing data to develop groundwater quantity and quality information for binational aquifers between Arizona, New Mexico, Texas and Mexico. The United States-Mexico Transboundary Aquifer Assessment Program completed the first year of the five-year program, however, no second-year funding was allocated.

Award No. 08HQAG0118 Transboundary Aquifer Assessment Program

Basic Information

Title:	Award No. 08HQAG0118 Transboundary Aquifer Assessment Program
Project Number:	2008TX353S
Start Date:	3/31/2008
End Date:	4/30/2011
Funding Source:	Supplemental
Congressional District:	
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Models, Hydrology
Descriptors:	
Principal Investigators:	Ari Michelson

Publications

1. Michelsen, A., B. Alley, Z. Sheng, P. King, M. Darr, S. Megdal, and F. Cafaggi Felix, 2011, Transboundary aquifer assessment program [Abstract], Panel at AWRA 2011 Annual Water Resources Conference, Albuquerque, New Mexico, November 7-10.
2. Sheng, Z., J.P. King, and J. Gastelum, 2011, Effects of Groundwater Pumping on the Stream Flow and Aquifer Storage in Mesilla Basin [Abstract], “in” Proc. Of World Environmental and Water Resources Conference, ASCE, Palm Springs, CA, May 21-26, 2011.

UNITED STATES – MEXICO TRANSBOUNDARY AQUIFER ASSESSMENT PROGRAM
ANNUAL REPORT 2011–2012
New Mexico and Texas Water Resources Research Institutes in Collaboration with USGS NM and TX State Offices

Description: This is a Congressionally-authorized program, Public Law 109-448, to conduct bi-national, scientific research to systematically assess priority transboundary aquifers. The results of this program will provide a scientific foundation for state and local officials to address pressing water resource challenges in the United States–Mexico border region. Investigations will be conducted in partnership with the U.S. Geological Survey (USGS), Texas and New Mexico Water Resources Research Institutes and in collaboration with appropriate state agencies and Mexican counterparts.

Relevance and Background: In the desert region of the border surface water is scarce and unreliable, making groundwater the primary—and in some areas, the only—water source. Declining aquifers and increasing use of border groundwater resources by municipal and other water users have raised serious concerns about long-term availability of this supply. Water quantity and quality are determining and limiting factors that ultimately control future economic development, population growth, and human health along the United States–Mexico border. However, knowledge about the extent, depletion rates, quality, and solute movement of transboundary aquifers is inadequate.

Objectives: The *United States–Mexico Transboundary Aquifer Assessment* Program objectives are to collect and evaluate new and existing data to develop high-quality, comprehensive groundwater quantity and quality information, and to develop groundwater flow models for selected priority binational aquifers in Arizona, New Mexico, Texas, and Mexico. This bi-national information is essential for understanding the extent of these aquifers and quantifying water availability, water quality, and use of these aquifers. Based on stakeholder input, the primary initial focus of the New Mexico and Texas assessment program is the Mesilla Basin aquifer in the El Paso, TX, Southern New Mexico and Ciudad Juarez, MX regions because of the reliance, rapidly expanding use, and immediate need for information regarding this aquifer. Through this program, scientists from New Mexico State University, The Texas A&M University System, University of Arizona, U.S. Geological Survey, state agencies, and Mexican counterparts are working in partnership to collect, share, and evaluate new and existing data to develop high-quality, comprehensive, groundwater quantity and quality data and groundwater flow models for bi-national aquifers. This information is needed to understand availability and use and to evaluate strategies to protect water quality and enhance water supplies for sustainable economic development on the United States–Mexico border.

Project Activity and Accomplishments:

Despite not receiving additional funding after March 2011, accomplishments and activities include:

a. Development of research plans in collaboration with stakeholders;

b. Review and evaluation of approximately 800 publications and previous studies on the Mesilla Basin and development of a database for bibliographical searches and sharing;
c. Review and assessment of existing geological, hydrogeologic monitoring data, ancillary databases, and geographic information systems (GIS) for the Mesilla Basin from different sources, such as U.S. Geological Survey, New Mexico Office of State Engineer, Texas Water Development Board, Paso del Norte Watershed Council as well as available Mexico data and information;
d. Evaluation and further development of existing hydrogeologic framework models;
e. Review of seven existing independent groundwater models for the Mesilla Basin aquifer to select which one/ones to use for bi-national aquifer modeling;
f. Identification of data gaps and additional information needed for hydrogeologic model development;
g. Development of a data sharing and program coordination agreement with Mexico through the U.S. and Mexico International Boundary and Water Commissions;
h. Preparation of a scope of work and funding proposal for research to be conducted in Mexico.
i. Finished Hydrological Report prepared by Mexican scientists sponsored in part by TWRI and NMWRRI.
j. Organized panel session on TAA program at American Water Resources Association in November 2011.
k. Prepared Congressional Interim Report required by the Act.

Partners:
Texas Water Development Board, El Paso Water Utilities, New Mexico State University, University of Arizona, USGS Texas State Office, Water Science Center, USGS New Mexico State Office Water Science Center, International Boundary and Water Commission–United States and Mexican Sections, and many others, including numerous water management agencies and organizations.

Hydrological Drought Characterization for Texas under Climate Change, with Implications for Water Resources Planning and Management

Basic Information

Title:	Hydrological Drought Characterization for Texas under Climate Change, with Implications for Water Resources Planning and Management
Project Number:	2009TX334G
Start Date:	9/1/2009
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	17th, TX
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Surface Water, Climatological Processes
Descriptors:	None
Principal Investigators:	Vijay P Singh, Ashok Kumar Mishra

Publications

1. Singh, V. P., 2010, Entropy theory for derivation of infiltration equations, Water Resources Reseach, 46, W03527, doi:10.1029/2009WR008193.
2. Singh, V. P., 2010, Entropy theory for movement of moisture in soils, Water Resources Research, 46, W03516, doi:10.1029/2009WR008288.
3. Mishra, A. K., and V. P., Singh, 2010, Changes in extreme precipitations in Texas, J. Geophysical Research, American Geophysical Union, (In Press). Manuscript no: 2009JD013398.
4. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Association between uncertainty in meteorological variables and water resources planning for Texas, Journal of Hydrologic Engineering, ASCE, (in press).
5. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Scaling characteristics of wet and dry spells of precipitation data, Journal of Hydrologic Engineering, ASCE, (In press).
6. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Long lead time drought forecasting using a wavelet and fuzzy logic combination model, Water Resources Research (Submitted after first review), American Geophysical Union, Manuscript no:2009WR008794.
7. Mishra, A. K., and V. P., Singh, 2010, A review on drought concepts, Journal of Hydrology, (Submitted after first review), Manuscript no: HYDROL 8529.
8. Mishra, A. K., and V. P., Singh, 2010, Drought modeling: A review, Reviews of Geophysics, (Submitted).
9. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Seasonal streamflow extremes in Texas River basins: Uncertainty, trends and teleconnections under climate change scenarios, Journal of Geophysical Research, (Submitted).
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11. Singh, V. P., 2010, Entropy theory for movement of moisture in soils, Water Resources Research, 46, W03516, doi:10.1029/2009WR008288.

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19. Mishra, A. K., Singh, V. P., and Özger, M., (2011). Seasonal streamflow extremes in Texas River basins: uncertainty, trends and teleconnections. Journal of Geophysical Research, AGU,116, D08108. doi:10.1029/2010JD014597.
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21. Ozger, M., Mishra, A. K., and Singh, V. P. (2011), Long lead time drought forecasting using a wavelet and fuzzy logic combination model. J Hydrometeorology (Submitted after first review), AMS. Manuscript no: JHM-D-10-05007.
22. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Scaling characteristics of precipitation data in conjunction with wavelet analysis. Journal of Hydrology, 395(3-4), 279-288.
23. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.
24. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.
25. Mishra, A. K., and Singh, V. P. (2010), A review of drought concepts. Journal of Hydrology, 391(1-2), 202-216.
26. Z. Hao., and V. P. Singh. (2011), Single-site monthly streamflow simulation using entropy theory, Water Resources Research (Resubmitted)
27. Long, D., and Singh, V.P. (2011), A two-source trapezoid model for evapotranspiration from satellite imagery, Remote Sensing of Environment (Under review).
28. Long, D., and Singh, V.P. (2011), How sensitive is SEBAL to changes in input variables, domain size and satellite sensor? Journal of Geophysical Research (Under review).
29. Long, D., and Singh, V.P. (2011), A Modified Surface Energy Balance Algorithm for Land (M-SEBAL) based on a trapezoidal framework, Water Resources Research (Under review).
30. Long, D., and Singh, V.P. (2011), Addressing the scale dependencies of remote sensing-based triangle models, Agricultural and Forest Meteorology (Under review).
31. Rajsekhar, D., Mishra, A. and Singh, V.P. (2011), Regionalization of annual hydrological drought severity for Neches river basin, IPWE, Singapore, Jan 4-6,2011.
32. Rajsekhar, D., Mishra, A. and Singh, V. P. (2011), Drought Regionalization of Brazos River using an entropy approach, Symposium on Data driven approaches to drought, Purdue University, West Lafayette, Indiana, June 21-22, 2011.
33. Singh, V. P., 2010, Entropy theory for derivation of infiltration equations, Water Resources Reseach, 46, W03527, doi:10.1029/2009WR008193.
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47. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.
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57. Long, D., and V.P. Singh, 2012, A modified surface energy balance algorithm for land (M-SEBAL) based on a trapezoidal framework, Water resources Research, Vol. 48, W02528, doi: 10.1029/2011WR010607.
58. Long, D., V.P. Singh, and Z.-L. Li, 2012, On the Scale Effects of SEBAL: Do the Variables and Performance of SEBAL Vary with Watersheds and Satellite Platforms? Remote Sensing of Environment, Vol. 121, pp. 370-388, 2012.
59. Long, D., V.P. Singh, and B.R. Scanlon, 2012, Deriving theoretical boundaries to address scale dependencies of triangle models for evapotranspiration estimation, Journal of Geophysical Research, Vol. 117, D05113, doi: 10.1029/2011JD017079, 2012.
60. Rajsekhar, D., A.K. Mishra, and V.P. Singh, 2012, Regionalization of drought characteristics using an entropy approach, Journal of Hydrologic Engineering, Special issue on droughts, under revision.
61. Ozger, M., A.K. Mishra and V.P. Singh, 2012, Seasonal and spatial variations in the scaling and correlation structure of streamflow data, Hydrologic Processes, in press.
62. Li, Chao, V.P. Singh, and A.K. Mishra, 2012, Entropy Theory-based Criterion for Hydrometric Network Evaluation and Design: Maximum Information Minimum Redundancy, Water Resources Research, American Geophysical Union, in press.
63. Li, Chao, V.P. Singh and A.K. Mishra, 2012, Simulation of Daily Precipitation Using a Hybrid Probability Distribution and Markov Chain, Water Resources Research, American Geophysical Union, 48, W03521, doi:10.1029/2011WR011446.
64. Ozger, M., A.K. Mishra and V.P. Singh, 2012, Long lead time drought forecasting using a wavelet and fuzzy logic combination model: a case study in Texas, Journal of Hydrometeorology, American Meteorological Society, 13, 284–297.
65. Mishra, A.K., V.P. Singh and M. Özger, 2011, Seasonal streamflow extremes in Texas River basins: uncertainty, trends and teleconnections, Journal of Geophysical Research-Atmosphere, American Geophysical Union, 116, D08108, doi:10.1029/2010JD014597.
66. Mishra, A.K. and V.P. Singh, 2011, Drought modeling: A review, Journal of Hydrology, 403 (1-2), 157-175.
67. Hao, Z. and V. Singh, 2012, Entropy based method for bivariate drought analysis, Journal of Hydrologic Engineering, in press.

Hydrological drought characterization for Texas under climate change, with implications for water resources planning

Project number: 2009TX334G

Progress report (Sep 2011 to May 2012)

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<u>Contents</u>

Hydrological drought characterization for Texas under climate change, with implications for water resources planning

1. Basic information

Title:	Hydrological drought characterization for Texas under climate change, with implications for water resources planning
Project number:	2009TX334G
Start Date:	September 1, 2009
End Date:	August 31, 2012
Funding source:	104G
Congressional District:	17th TX
Research Category:	Climate and Hydrologic Processes.
Focus Categories:	Drought (DROU), Surface water (SW), Climatological processes (CP)
Descriptors:	Hydrological drought, Climate change, Critical basin, Teleconnection.
Principal investigator(s):	Vijay P. Singh and Ashok K. Mishra

2. Publications

Long, D., Singh, V.P. and Li, Z.- L.2011. How sensitive is SEBAL to changes in input variables, domain size and satellite sensor? Journal of Geophysical Research, Vol. 116, D21107, doi: 10.1029/2011JD016542.

Long, D., and Singh, V.P., 2012. A modified surface energy balance algorithm for land (M-SEBAL) based on a trapezoidal framework. Water resources Research, Vol. 48, W02528, doi: 10.1029/2011WR010607.

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Long, D., Singh, V.P. and Scanlon, B.R., 2012. Deriving theoretical boundaries to address scale dependencies of triangle models for evapotranspiration estimation. Journal of Geophysical Research, Vol. 117, D05113, doi: 10.1029/2011JD017079, 2012.

Rajsekhar,D., Mishra, A.K. and Singh, V.P. (2012). "Regionalization of drought characteristics using an entropy approach," Journal of hydrologic Engineering, Special issue on droughts (Under Revision).

Ozger, M., Mishra, A. K., and Singh, V. P. (2012), Seasonal and spatial variations in the scaling and correlation structure of streamflow data. Hydrologic Processes (In Press).

Chao Li., Singh, V. P., Mishra, A. K. (2012). Entropy Theory-based Criterion for Hydrometric Network Evaluation and Design: Maximum Information Minimum Redundancy. Water Resources Research, American Geophysical Union, (In Press).

Chao Li., Singh, V. P., Mishra, A. K. (2012). Simulation of Daily Precipitation Using a Hybrid Probability Distribution and Markov Chain. Water Resources Research, American Geophysical Union, 48, W03521, doi:10.1029/2011WR011446. [

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Hao, Z. and V. Singh (2012), Entropy based method for bivariate drought analysis, Journal of Hydrologic Engineering, in press

3. Problem and Research objectives

Droughts in the United States result in an estimated average annual damage of $6 to 8 billion (Wilhite, 2000). The estimated loss from the 1988 drought was $40 billion (American Meteorological Society, 1997) and the estimated loss for the state of Texas alone from the 1996 drought was $6 billion (Wilhite, 2000). Like other western states, Texas is a water deficient state and is highly vulnerable to droughts, and its vulnerability is being compounded by rapidly growing population. According to the Water Plan (*Water for Texas 2007*) developed by Texas Water development Board, water shortages during droughts could cost businesses and workers in the state about $98.4 billion by 2060 and about 85 percent of the state's projected population would not have enough water by 2060 in drought conditions), if an additional 8.8 million acre-feet of water supplies are not developed. Further complicating the Texas water shortage is climate change, which is being much debated these days. The major concern arising from climate change is its effect on water resources in terms of droughts and the resultant impact on different sectors. The objective of the project is therefore threefold:

(i) Analysis of multivariate hydrologic droughts: Drought is characterized by severity, areal extent, and duration. Multivariate distributions of these characteristics are needed and they will be derived using copulas. Then, droughts will be characterized by constructing: (a) Severity – Duration – Frequency curves (SDF), (b) Severity – Area – Frequency (SAF) curves, and (c) Severity-Interarrival time Frequency (SIF) curves. These curves are important for water resources planning.

(ii) Assessment of drought risk under climate change: Climate change impact studies have been conducted using a top-down approach. First, outputs from Global Circulation Models (GCMs) are considered which are downscaled in a second step to the river basin scale using either a statistical/empirical or a dynamic approach. The local weather scenarios are then statistically linked to possible large-scale climate conditions that are available from GCMs. Finally the downscaled meteorological variables are used as input to a macro scale land surface hydrologic model (i.e., VIC model) for investigating future hydrological drought scenarios. Several questions will be addressed: (a) How much percentage of a basin will undergo a drought in year 2050? (b) What will be the severity of the 2050 drought? (c) Will the drought of 2050 be more severe than the 2020 or 2080 drought? (d) What will be the duration of the drought in 2050 or 2080? (e) How much will be the water deficit in a river in 2050, considering it as a hydrological drought? (f) How will drought properties vary, when compared to the past 50 years? This objective will also attempt to quantify uncertainties in drought characterization, considering primarily climate change and different water management strategies.

(iii) Understanding of low frequency climate variations in association with Southern Oscillation Index (SOI) and Nino indexes: These variations affect Texas and their understanding will help provide improved streamflow forecasting needed for reservoir operations and will aid water management decisions. The lead-time of forecasting will be annual.

4. Principal findings and significance

The research findings are highlighted with three broad objectives: (a) entropy based regionalization of Texas based on drought severity and duration, (b) drought atlas for the state of Texas for different severities, durations and recurrence intervals, (c) simulating hydrological drought properties at different spatial units based on wavelet-Bayesian regression approach, and (d) research on evaporation

4 (a) Entropy based regionalization of Texas based on drought characteristics

Introduction: A homogenous region can be defined as a group of stations with similar probability distribution functions of drought properties (Mirakbari et al., 2010). The common concept used in regional analysis of droughts is to classify weather stations that exhibit similarities in a statistical sense. There are several methods for performing regionalization. Selection of a suitable similarity measure is important in clustering. Mostly, clustering techniques use a simple linear measure like Pearson correlation as a similarity measure for grouping. In this study, we explore the possibility of using a mutual information based index known as Directional Information Transfer (DIT) for identification of homogenous regions. This measure is not only sensitive to non-linear dependencies, but it is also unique due to its information theory background (Kraskov, 2009). It has a three-fold advantage over other dependence measures in that it gives an idea about: (1) information content at a station, (2) amount of information transferred between stations and the amount lost, and (3) relationships among stations based on information transmission characteristics (Yang and Burn, 1994).
The study basically focuses on understanding the spatial distribution of drought characteristics. An areal zoning of the study region based on various drought properties was conducted using a methodology based on entropy theory for Texas. The methodology is based on an index developed by Yang and Burn (1994) for design of data collection network. The same principle has been extended for grouping of stations. The application of this method is not explored till now in the context of regionalization.

Model and data used: A land surface model called Variable Infiltration Capacity (VIC) model (Liang et al., 1996) , was used to simulate stream flow for a period of 1950-2000. This particular model was chosen, since it focuses on simulating hydrological processes relevant to the water and energy balance over the land surface for studying the effects of climate changes on stream flow generation. Distinguishing characteristics of the model include the sub-grid variability in land surface vegetation classes, sub-grid variability in the soil moisture storage capacity, and drainage from the lower soil moisture zone (base flow) as a nonlinear recession. The variable infiltration capacity (VIC) model has been well calibrated and applied in a number of large river basins over the continental US and the globe, and has participated in the World Climate Research Program (WCRP) Intercomparison of Land Surface Parameterization Schemes (PILPS) project and the North American Land Data Assimilation System (NLDAS), where it has performed well relative to other schemes and to available observations (Bowling et al. 2003a, 2003b, Lohmann et al., 1998). The VIC-3L is a large scale land surface model and is used for simulating land-atmosphere fluxes by solving water and energy balance at a daily or sub-daily temporal scale (Liang et al., 1994). The land surface is essentially divided into grids of specified resolution. Each of these cells will be simulated independent of each other. Land surface is divided into different vegetation covers in such a way that multiple vegetation classes can exist within a cell. The soil moisture distribution, infiltration, drainage between soil layers, surface runoff, and subsurface runoff are all calculated for each land cover tile at each time step. Then, for each grid cell the total heat fluxes (latent heat, sensible heat, and ground heat), effective surface temperature, and the total surface and subsurface runoff are obtained by summing over all the land cover tiles weighted by fractional coverage.

For this study, the VIC model for stream flow simulation was run at $1/8^{th}$ degree resolution and hence all input files, including forcing files, soil and vegetation parameters have this resolution. This resolution was chosen by also taking into consideration the availability of gridded daily forcing data of precipitation (mm), maximum and minimum temperature (^{o}C) and wind speed (m/s) which is needed to drive the model, at $1/8^{th}$ resolution from Maurer et al. (2002) who has provided a data base for 15 delineated basins in the United States, Canada and Mexico. The time period of data used was the latter half of the 20^{th} century: 1949-2000. The year 1949-1950 was considered as the spin up year for the model. Apart from forcing data, soil and land cover data is also required by the VIC model. The soil characteristics which will not be considered for calibration were taken from gridded 1/8 degree datasets developed as part of the Land Data Assimilation System (LDAS) project (Mitchell et al. 1999). Vegetation parameters needed were also obtained from LDAS. Land cover characterization was based on the University of Maryland global vegetation classifications described by Hansen et al. (2000), which has a spatial resolution of 1 km, and a total of 14 different land cover classes. From these global data we identified the land cover types present in each 1/8 grid cell in the model domain and the proportion of the grid cell occupied by each, as described by Maurer et al. (2001). The leaf area index (LAI) needed was derived from the gridded (1/4 degree) monthly global LAI database of Myneni et al. (1997), which is inverted using the Hansen et al. (2000) land cover classification to derive monthly mean LAIs for each vegetation class for each grid cell. The data needed for the routing scheme includes a fraction file, flow direction file, Xmask file, flow velocity and diffusion files, and unit hydrograph file. ArcMap was used for the preparation of files, and the DEM files needed for creating the required files were obtained from the USGS hydro 1k datasets.

Methodology:

Step 1: Drought classification using standardized streamflow index (SSFI)

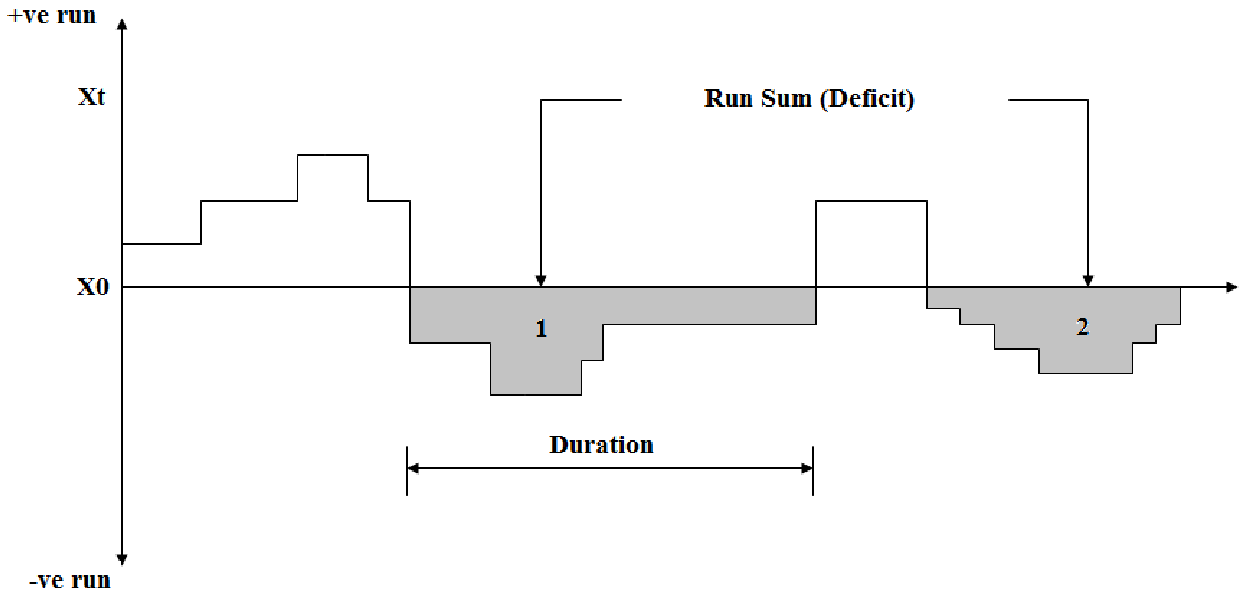


Figure 1. Drought Characteristics using the theory of runs

Figure 1 describes drought characteristics for a drought event using the theory of runs. A drought event is characterized by severity, duration and magnitude (Mishra and Singh, 2010). For any drought event, the cumulative deficit of the variable of interest during the drought event is defined as drought severity. Drought duration is the time between the onset and the end of a drought event. Drought magnitude is the average deficit per unit duration. In this study, drought duration and severity were considered.

The theory of runs was used for deriving drought characteristics from the stream flow time series. This method has been widely used in the field of hydrology. Yevjevich et al. (1967), Rodriguez-Iturbe (1969), Saldarriaga and Yevjevich (1970), Millan and Yevjevich (1971), Guerrero-Salazar and Yevjevich (1975), and Sen (1976, 1977) are among the first few who applied the run theory in hydrology. A run is defined as a portion of time series of drought variable X_t in which all values are either above or below a threshold level X_0. Accordingly, it can be called a positive or a negative run. The threshold level may be constant or it may vary with time. Thus, the drought characteristics essentially depend upon the threshold chosen (Mishra and Singh, 2010). In this study, the drought variable chosen was standardized stream flow index (SSFI). The concept of SSFI is statistically similar to that of standardized precipitation index (SPI) introduced by McKee (1993) and has been applied by Modarres (2007). Shukla and Wood (2008) used a standardized runoff index (SRI) as a complement to the SPI to assess hydrological aspects of a drought. Table 1 gives the classification of events based on the SSFI values (Modarres, 2007).

Table 1. SSFI Classification

SSFI value	Classification
2.0 or more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 or less	Extremely dry

Following this classification, a threshold value of -0.99 was chosen, since any value below that indicates the onset of a dry event.

The calculation of SSFI involves the following steps: (1) A suitable probability distribution is fitted to the monthly stream flow time series for the time period 1950-2000. (2) From the fitted frequency distribution, the cumulative probability distribution of stream flow is obtained. (3) Cumulative probability is transformed to a standard normal variate of zero mean and unit standard deviation. This will be calculated from a numerical approximation to the normal cumulative distribution function (CDF). The approximation given by Abramowitz and Stegun (1964) was used to obtain the standard normal probability distribution function (PDF). The approximation for $\phi(x)$ for $x>0$ is given by:

$$\phi(x) = 1 - \varphi(x)(b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5) + \varepsilon(x), \quad t = \frac{1}{1 + b_0 x} \tag{1}$$

where $\varphi(x)$ is the standard normal PDF, b_0=0.2316419, b_1=0.319381530, b_2=-0.356563782, b_3=1.781477937, b_4=-1.821255978, b_5=1.330274429. This is the z-score and conceptually it represents the number of standard deviations above or below that an event is from the mean (McKee, 1993). Thus, essentially SSFI for a given series is given as:

$$SSFI = \frac{F_i - \bar{F}}{\sigma} \tag{2}$$

where F_i is the flow rate in time interval i, $\bar{F}$ is the mean of the series, and σ is the standard deviation of the series.

In this study, for each of the five climatic regions, considering a number of previous studies, like Zaidman et al. (2001), Kroll and Vogel (2002), McMahon et al. (2007), Shukla and Wood (2008) and Nalbantis and Tsakiris (2009), the log-normal distribution was selected for fitting monthly stream flow data. The two parameter log normal distribution was found to fit well for all the stations considered. The quantile plots and Kolmogorov-Smirnov (K-S) test were considered for assessing the goodness of fit. Table 2 gives the list of USGS stations considered for validation of the VIC model results. Table 3 gives the results of the K-S test for the goodness of fit at the 5%

significance level. The quantile – quantile plot for two parameter log normal distribution used to fit stream flow at the selected stations (Figure 2).

Table 2. Information on validation stations within Texas

Station Name	Station ID	Latitude	Longitude	Validation Period	Climate Zone
Pecos Rv at Pecos	8420500	31.436	-103.467	1951-1952	Arid
Canadian Rv Nr Amarillo	7227500	35.471	-101.88	1981-1982	Continental
Pr Dog Twn Fk Red Rv nr Wayside	7297910	34.837	-101.414	1968-1969	Continental
Canadian Rv Nr Canadian	7228000	35.935	-100.371	1965-1966	Continental
Independence Ck Nr Sheffield	8447020	30.452	-101.733	1975-1976	Semiarid
Nueces Rv Nr Asherton	8193000	28.5	-99.682	1959-1960	Semiarid
Colorado Rv Nr Gail	8117995	32.628	-101.285	1989-1990	Subtropical Semi humid
Colorado Rv Nr Stacy	8136700	31.494	-99.574	1969-1970	Subtropical Semi humid
Millers Ck Nr Munday	8082700	33.329	-99.465	1972-1973	Subtropical Semi humid
Medina Rv Nr Macdona	8180700	29.335	-98.689	1982-1983	Subtropical Semi humid
Cowhouse Ck at Pidcoke	8101000	31.285	-97.885	1955-1956	Subtropical Semi humid
Perdido Ck at M 622 Nr Fannin	8177300	28.752	-97.317	1979-1980	Subtropical Semi humid
Los Olmos Ck Nr Falfurrias	8212400	27.2645	-98.136	1967-1968	Subtropical Semi humid
Lake Fk Ck Nr Quitman	8019000	32.763	-95.463	1982-1983	Subtropical humid
Kickapoo Ck Nr Onalaska	8066170	30.907	-95.088	1991-1992	Subtropical humid
Vince Bayou at Pasadena	8075730	29.6947	-95.216	1973-1974	Subtropical humid

Table 3. Values of the Kolmogorov-Smirnov test at 5 percent significance level for two parameter log-normal distribution at selected stations

Station	Climate zone	p-value	k-s stat
ID 08101000	Subtropical Semi humid	0.0735	0.1280
ID 07227500	Continental	0.0684	0.2629
ID 08193000	Semiarid	0.0738	0.2546
ID 08420500	Arid	0.5500	0.1267
ID 08019000	Subtropical humid	0.4597	0.1689

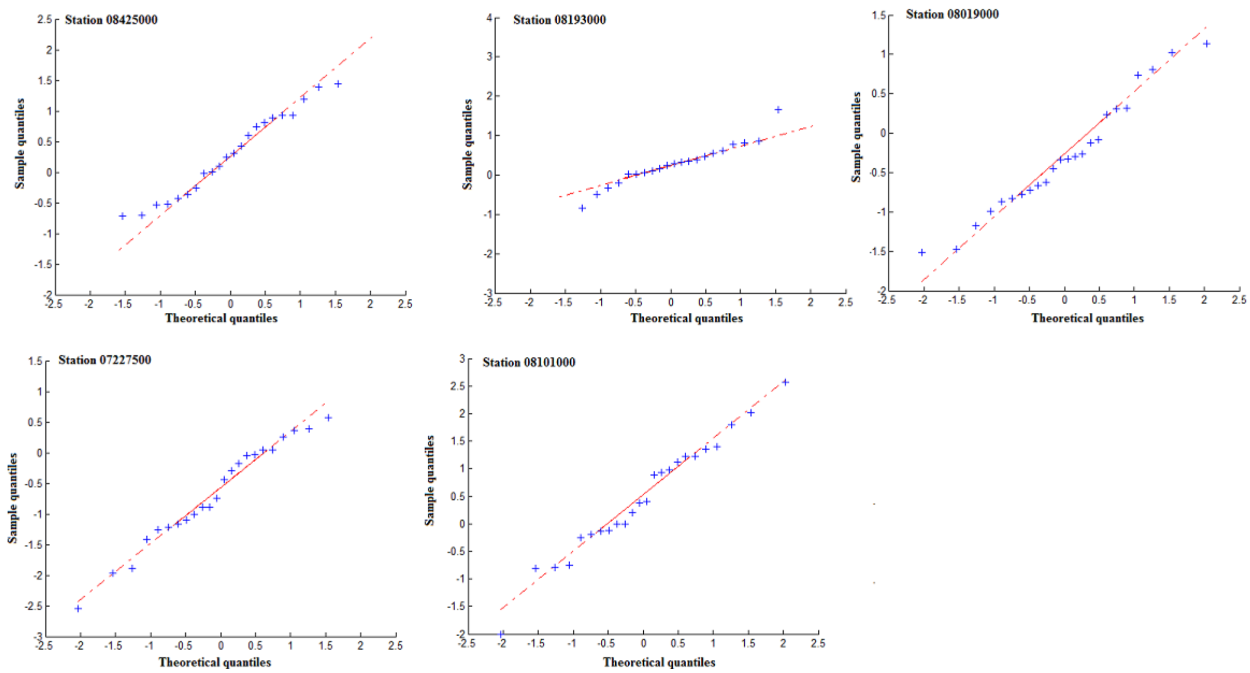


Figure 2. QQ plots for two parameter log normal distribution used to fit stream flow at selected stations

Step 2. Regionalization based on directional information transfer (DIT)

Regionalization is the process of identifying homogenous regions. In this context, a homogenous region comprises an area which has similar hydrologic response. This is generally done by grouping similar objects. In this study, an entropy based index, known as directional information transfer (DIT), was used for the grouping of grids into homogenous regions. This index is based on mutual information which measures information transfer among the stations. Entropy can be used to measure the information content of observations and mutual information can be used to measure the information transfer. Thus entropy and mutual information provide a threefold measure of information at a station, information transfer and loss of information between stations, and description of relationships among stations according to the information transfer between them (Yang and Burn, 1994).

Entropy concepts

Entropy, first introduced in the field of information theory by Shannon (1948), is defined for a random variable X as (Lathi,1968):

$$H(X) = \sum_{i=1}^{k} P(x_i) \log_2 P(x_i) \quad (3)$$

where $P(x_i)$'s are the probabilities associated with the events $X=x_i$, and k denotes the total number of class intervals or bins. $H(X)$ is the marginal entropy of X, which means the measure of information contained in X. If two random variables (X,Y) are considered, the mutual information or the measure of information transfer between them can be computed as (Lathi, 1968):

$$T(X,Y) = H(X) - H(X \mid Y) \quad (4)$$

where $H(X|Y)$ represents the information lost during transmission which can be estimated as:

$$H(X \mid Y) = \sum_{i,j} P(X_i, Y_j) \log_2 \frac{P(X_i, Y_j)}{P(Y_j)} \quad (5)$$

where $P(X_i, Y_j)$ is the joint probability distribution and $P(Y_j)$ is the marginal distribution of random variable Y, i and j denotes the class intervals corresponding to X and Y, respectively.

When comparing objects with different marginal or joint pieces of information, one should preferably use a relative measure rather than an absolute one, so as to minimize the dependence on total information (Kraskov et al., 2005). Hence, mutual information should be standardized to form an index known as directional information transfer (DIT). Directional information transfer is the fraction of the information transferred from one site to another. It is a normalized version of mutual information between two gauges to obtain the fraction of information transferred from one site to another as a value between 0 and 1. DIT is a much better index than mutual information because the upper bound of mutual information can vary from site to site, depending on the marginal entropy value at the respective station which makes the mutual information a not so good index of dependence. DIT can thus be expressed as:

$$DIT_{xy} = \frac{T(X,Y)}{H(X)};\ DIT_{yx} = \frac{T(X,Y)}{H(Y)} \quad (6)$$

where DIT_{xy} describes the fractional information inferred by station X about Y, and DIT_{yx} is the fractional information inferred by station Y about X ; $T(X,Y)$ is the mutual information between X and Y; and $H(X)$ and $H(Y)$ are the marginal entropy values for X and Y, respectively. Since $H(X|Y)$ is equivalent to the loss of information H_{lost}, the DIT can be rewritten as:

$$DIT = (H - H_{lost}) / H = 1 - (H_{lost} \mid H) \quad (7)$$

It should also be noted that while the mutual information term is symmetric, DIT is no longer symmetric.

Regionalization using DIT

While using DIT for regionalization, those stations for which both DIT_{xy} and DIT_{yx} are high can be considered to be strongly dependent, since information can be mutually inferred between them. If neither DIT is high, then the two stations should remain in separate groups. If only one DIT is high, say DIT_{xy}, then station *Y*, whose information can be predicted by *X*, can join station *X* if station *Y* does not belong to any other group; otherwise it stays in its own group. But, by no means can *X* enter station *Y*'s group (Yang and Burn, 1994). The number of groups formed is controlled by the threshold value of DIT. A higher threshold value will lead to a larger number of groups. However, the size of each group will be small. A lower threshold value will result in the formation of a small number of groups, but the size of each group will be larger. There is no rule based on which the threshold of DIT can be fixed, and hence is case specific.

There were a total of 4174 grids of 1/8 degree size, which covers the state of Texas. The number of regions formed depends upon the threshold value of DIT. Table 4 shows the number of groups formed, while the threshold value of DIT was varied for drought severity and duration.

Table 4. Number of regions formed by varying thresholds

Drought Severity		**Drought Duration**	
Threshold DIT	**Number of Regions**	**Threshold DIT**	**Number of Regions**
0.2	4	0.15	3
0.25	5	0.3	5
0.35	7	0.45	6
0.5	8	0.55	9

Since a DIT value higher than 0.5 ensures a good information connection between two grids and higher values yield a large number of groups, eight regions based on drought severity, and nine regions based on drought duration were chosen. The corresponding threshold value of DIT was 0.5 for regions based on severity and 0.55 for regions based on duration.

Step 3. Regional homogeneity test

To check the heterogeneity of the regions obtained, the test suggested by Hosking and Wallis (1993, 1997) was performed. This test aims at estimating the degree of heterogeneity among the grouped sites and then assessing whether it is reasonable to treat it as a homogenous region or not. Three heterogeneity measures (HM) were devised and the values of HM should ideally be less than 1 for the regions to be considered as acceptably homogenous, and between 1 and 2 to be considered as possibly homogenous. If the value of HM is greater than or equal to 2, the region is definitely heterogeneous. The first HM, H_1, is based on the L-coefficient of variation (L-CV), the second HM, H_2, is based on L-CV and L-skewness and the third measure H_3 is based on L-skewness and L-kurtosis and they are given as:

$$H_1 = \frac{(V - \mu_{V_1})}{\sigma_{V_1}} \quad H_2 = \frac{(V_2 - \mu_{V_2})}{\sigma_{V_2}} \quad H_3 = \frac{(V_3 - \mu_{V_3})}{\sigma_{V_3}} \qquad (8)$$

where

$$V = \left(\frac{\sum_{i=1}^{N} n_i (t_i - t_R)^2}{\sum_{i=1}^{N} n_i} \right)^{1/2} \tag{9}$$

$$V_1 = \left(\frac{\sum_{i=1}^{N} n_i \left\{ (t_i - t_R)^2 + (t_{3i} - t_{3R})^2 \right\}^{1/2}}{\sum_{i=1}^{N} n_i} \right) \tag{10}$$

$$V_2 = \left(\frac{\sum_{i=1}^{N} n_i \left\{ (t_{3i} - t_{3R})^2 + (t_{4i} - t_{4R})^2 \right\}^{1/2}}{\sum_{i=1}^{N} n_i} \right) \tag{11}$$

where n_i is the record length at the i^{th} grid considered out of a total of N grids, and t_i, t_{3i} and t_{4i} are the L-CV, L-skewness and L-kurtosis at the respective grid, whereas t_R, t_{3R}, and t_{4R} stand for the weighted average of L-CV, L-skewness and L-kurtosis, respectively, for the entire region under consideration. Here V, V_1 and V_2 are the statistics for the 'real' region, V is the weighted standard deviation of L-CVs at the site, V_1 is the weighted average distance from the site to the group weighted mean in a two-dimensional space of L-CV and L-skewness, and V_2 is the weighted average distance from the site to the group weighted mean in a two-dimensional space of L-skewness and L-kurtosis (Srinivas et al., 2008). the region is considered to be acceptably homogeneous if H_1<1, possibly homogeneous if H_1 is between 1 and 2, and definitely heterogeneous if H_1 is greater than or equal to 2 (Hosking and Wallis, 1997).

Following the procedure mentioned in the second step, once the regions were formed based on the chosen threshold, the next step was to check for their meaningfulness. The L-moments based the heterogeneity test by Hosking and Wallis (1997) was used for this purpose. To improve the homogeneity of a region, the discordant sites within each region were identified by computing a discordance measure. Any station which had a discordant measure value more than 3 was shifted to another region, provided the other region remained homogeneous even after the transfer. If the aforementioned condition was not satisfied, a site cannot be allocated to any other region, and hence it would be eliminated. Tables 5 and 6 give details of the discordant sites within the regions formed based on DIT for drought severity and duration, respectively. Tables 7 and 8 show the heterogeneity measures for the regions after elimination or shifting of discordant sites.

Table 5. Discordant sites in the regions formed based on drought severity

Region	Number of discordant sites	Adjustments
Region 1	8	4 deleted 4 moved to Region 4
Region 2	7	3 deleted 4 moved to Region 3
Region 4	0	-
Region 5	0	-
Region 6	9	2 moved to Region 4 1 moved to Region 5 6 moved to Region 7
Region 7	12	4 deleted 4 moved to Region 4 1 moved to Region 6 3 moved to Region 8
Region 8	8	4 deleted 2 moved to Region 5 2 moved to Region 6

Table 6. Discordant sites in the regions formed based on drought duration

Region	Number of discordant sites	Adjustments
Region 1	9	5 deleted 1 moved to Region 2 1 moved to Region 3 2 moved to Region 5
Region 2	4	4 deleted
Region 3	0	-
Region 4	13	7 deleted 1 moved to Region 3 3 moved to Region 5 2 moved to Region 8
Region 5	5	3 deleted 2 moved to Region 1
Region 6	5	2 deleted 1 moved to Region 5 2 moved to Region 8
Region 7	6	2 deleted 2 moved to Region 8 2 moved to Region 9
Region 8	4	2 deleted 2 moved to Region 6
Region 9	0	-

Table 7. Heterogeneity measures for the regions based on drought severity

Region	H_1	H_2	H_3	Conclusion
Region 1	-1.03	-1.68	0.352	Acceptably homogeneous
Region 2	-1.299	-3.09	1.14	Possibly homogeneous
Region 3	-1.332	0.376	0.241	Acceptably homogeneous
Region 4	-1.325	-1.698	0.189	Acceptably homogeneous
Region 5	-1.670	-8.703	-1.658	Acceptably homogeneous
Region 6	-2.176	-7.469	0.924	Acceptably homogeneous
Region 7	-1.481	-1.125	-1.636	Acceptably homogeneous
Region 8	-1.346	-1.008	-1.475	Acceptably homogeneous

Table 8. Heterogeneity measures for the regions based on drought duration

Region	H_1	H_2	H_3	Conclusion
Region 1	-2.514	0.894	0.722	Acceptably homogeneous
Region 2	-2.159	0.935	0.639	Acceptably homogeneous
Region 3	-2.682	0.946	0.644	Acceptably homogeneous
Region 4	-3.034	0.575	0.477	Acceptably homogeneous
Region 5	-2.477	-3.520	-2.205	Acceptably homogeneous
Region 6	-2.176	-7.469	0.924	Acceptably homogeneous
Region 7	-1.481	-1.125	-1.636	Acceptably homogeneous
Region 8	-1.162	-5.728	-4.716	Acceptably homogeneous
Region 9	-2.265	0.355	0.983	Acceptably homogeneous

Figures 3 and 4 show the homogenous regions formed based on the drought severity and drought duration, respectively.

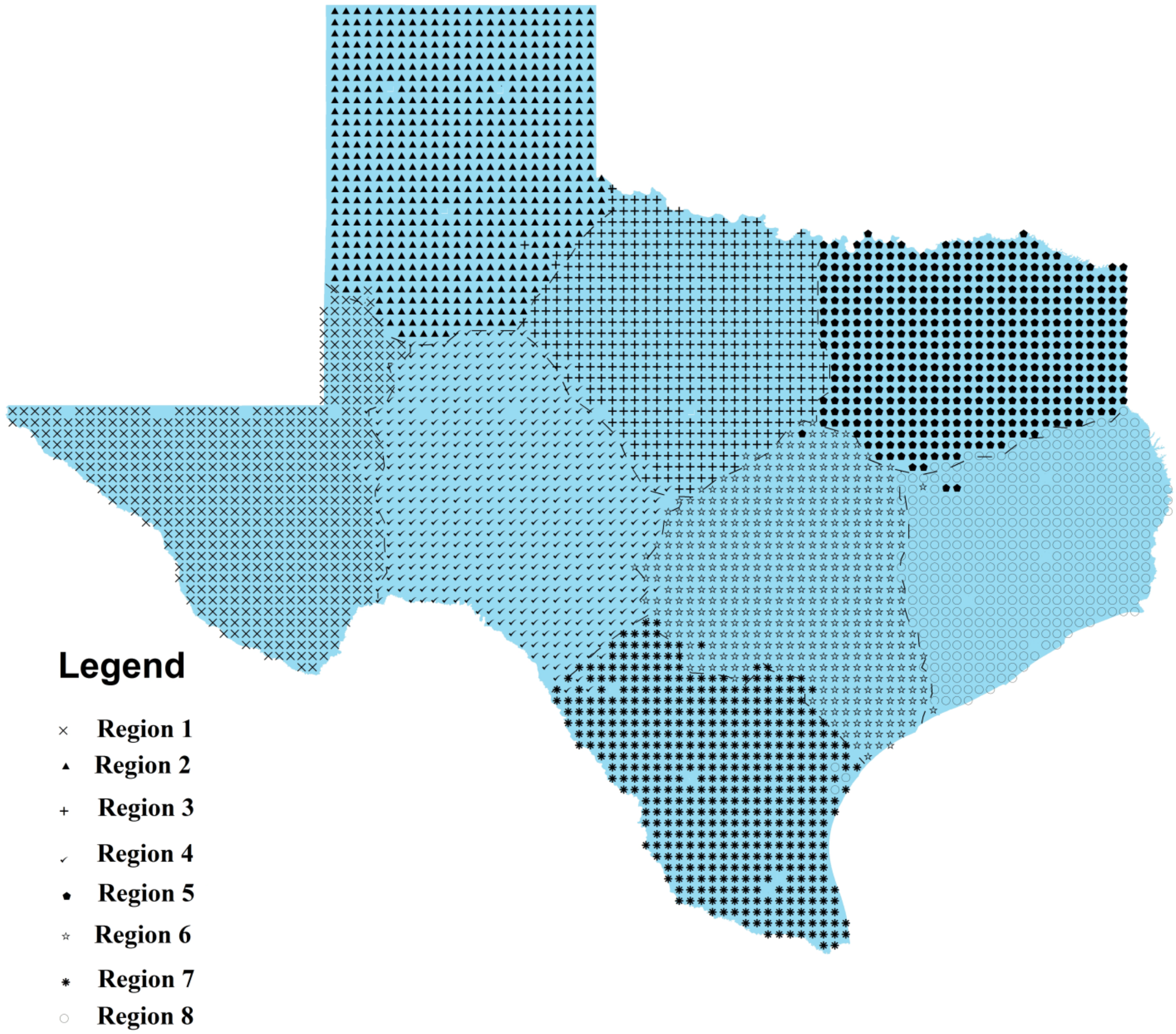


Figure 3. Homogenous regions formed using DIT based on drought severity

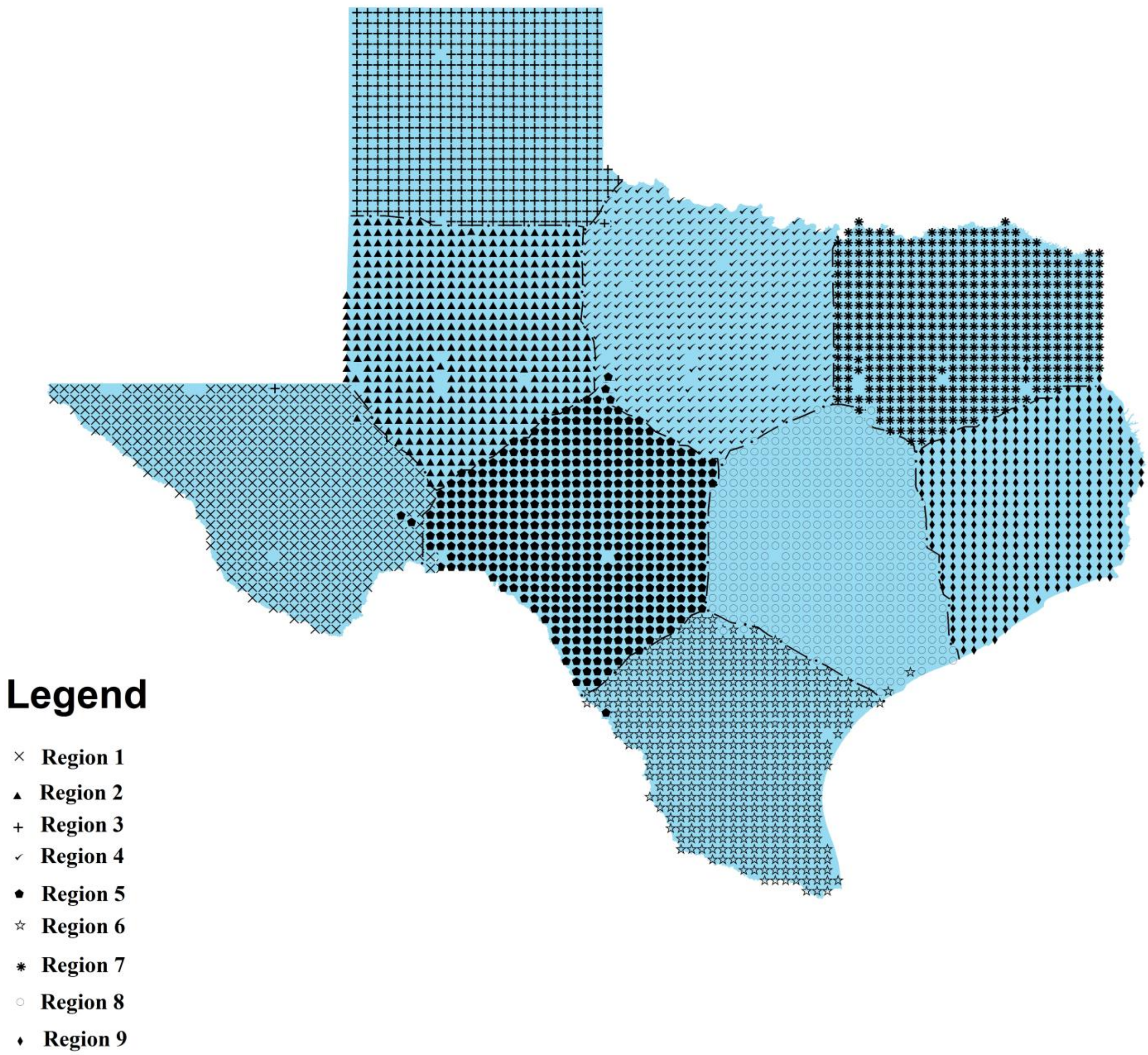


Figure 4. Homogeneous regions formed based on drought duration

Tables 9 and 10 give details of the regions based on severity and duration, respectively.

Table 9. Details of the regions formed based on drought severity

Region	Number of grids	Percentage Area covered	Annual average severity
1	478	11.495	7.65
2	489	11.761	7.219
3	658	15.824	6.294
4	574	13.804	6.632
5	550	13.227	7.074
6	483	11.616	5.435
7	453	10.895	5.346
8	473	11.375	4.898

Table 10. Details of homogenous regions formed based on drought duration

Region	Number of grids	Percentage Area covered	Average drought duration in months
1	499	11.11	73
2	462	10.52	64
3	498	12.02	58
4	485	9.13	47
5	484	10.51	77
6	436	11.69	91
7	437	11.37	33
8	473	12.01	42
9	379	11.66	27

The study can be extended to the bivariate case too, where both the drought severity and duration will be considered simultaneously for regionalization. The procedure followed for the bivariate case will be similar to the univariate case. However, the calculation of joint probabilities will be more complicated, since a four dimensional contingency table would be required for the same. The threshold value considered was 0.4, corresponding to which a total of five homogeneous regions were formed for the bivariate case. Table 11 gives the details of the heterogeneity measures for the five regions formed for the bivariate case. Figure 5 shows the homogeneous regions formed for the bivariate case. The details of each of the region are given in Table 12.

Table 11. Heterogeneity measures for the regions formed in the bivariate case

Region	H_1	H_2	H_3	Conclusion
Region 1	0.839	1.023	0.764	Possibly homogeneous
Region 2	-1.173	0.927	0.873	Acceptably homogeneous
Region 3	0.026	0.583	0.698	Acceptably homogeneous
Region 4	0.905	0.884	0.329	Acceptably homogeneous
Region 5	0.926	1.183	0.547	Possibly homogeneous

Table 12. Details of homogenous regions formed based on drought severity and duration

Region	Number of grids	Percentage Area covered	Annual average severity	Average drought duration in months
1	759	18.45	6.714	87
2	790	19.20	7.937	75
3	694	16.87	6.717	51
4	874	21.24	7.169	54
5	997	24.23	4.814	30

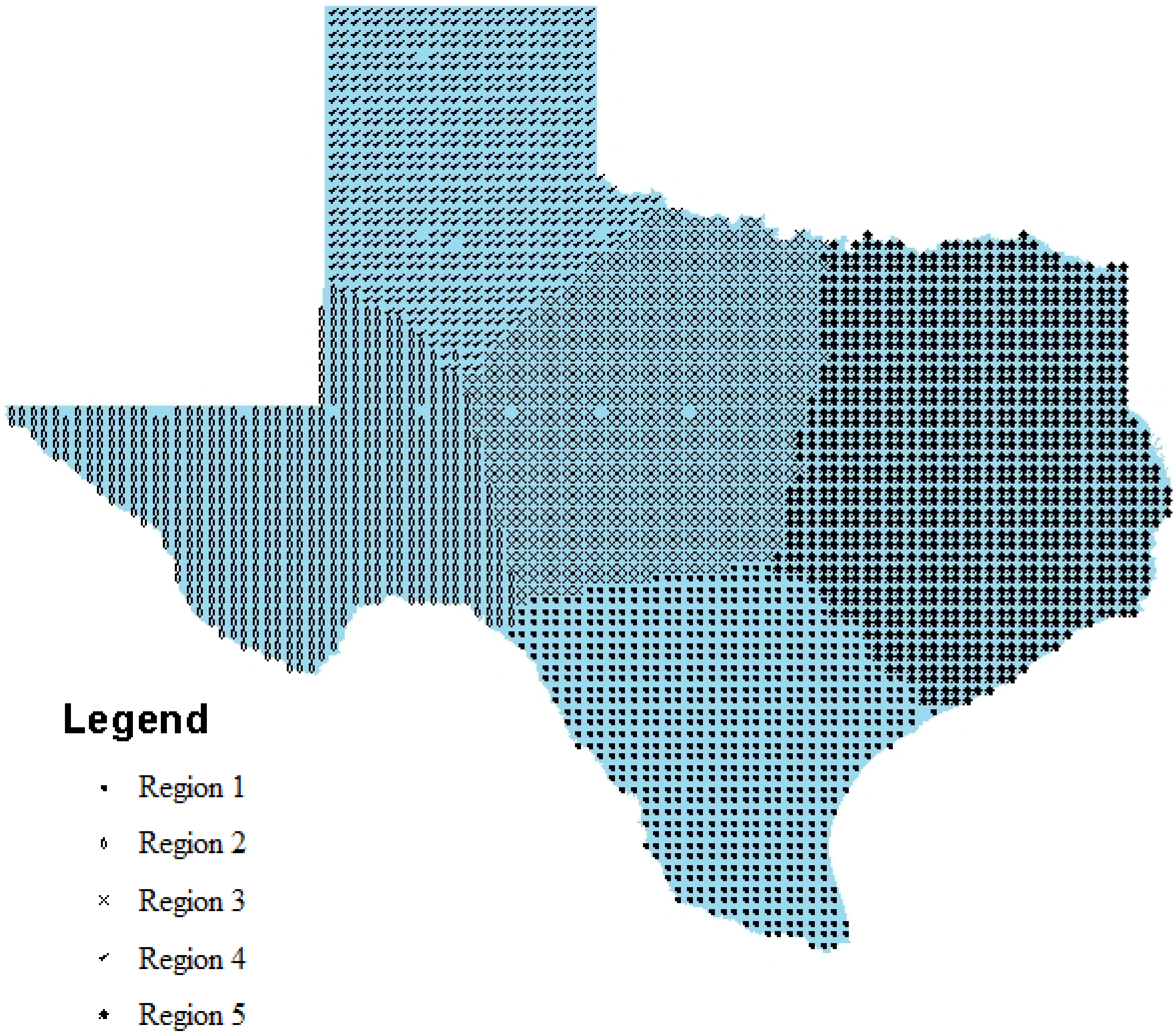


Figure 5. Homogeneous Regions formed in the bivariate case

Conclusions derived:

An entropy based similarity measure known as directional information transfer (DIT) is used to regionalize the state of Texas based on drought severity and duration. This measure, being more sensitive to nonlinear dependencies, is a better similarity measure than the commonly used linear dependence measures. By making use of the non-symmetric property of the index, if there is a great difference between the DIT_{xy} and DIT_{yx} values of a station pair, it can imply that given the observations at one station, the response at the other station is ambiguous. This can be due to greater loss during information transfer. It should however be noted that no strict guidelines are available for fixing a threshold value for the DIT. This is expected, since regionalization is essentially a subjective process, and hence, in any case the threshold will be user defined provided that the value is not too high (which may lead to strong dependence between stations belonging to different regions) or too low (which may lead to low dependence between stations within the same region). Finer adjustments can be made to the threshold value by observing how a change in its value affects the number and size of the regions formed. The following conclusions are drawn from the study:

1. DIT can satisfactorily identify homogeneous regions based on drought severity and duration, thus leading to the classification of Texas into zones based on stream flow drought properties.
2. Identification of critical regions in a drought prone state like Texas is done by assessing drought properties within each region formed. Region 1 lying within the Trans Pecos zone in the west Texas is the most critical region in terms of severity. Region 8 which lies in the eastern part of Texas has the lowest severity. The pattern is consistent with the precipitation pattern in Texas. As far as drought duration is concerned, region 6 which lies in south Texas, south central Texas and Lower Valley has the longest drought duration. Region 9 which lies in the eastern Texas has the lowest drought duration.
3. Parts of High Plains, Upper Coast, central and western Texas are affected by moderately dry droughts. However, severely dry and extremely dry droughts are mainly restricted to western, central and south Texas.

The study can be extended to bivariate case too. The stream flows at the USGS gauges are controlled/observed flow. The model has been calibrated and validated on the basis of the original controlled/observed flow instead of naturalized flow. This might have an impact on the runoff simulations obtained from the model. It might not be possible for any model to accurately reproduce the real world scenario for the runoff production process. However, it should be noted that the model simulations does show a satisfactory correlation with the original stream flow, and that the model in general underpredicts stream flow values in comparison to the original values. As an extension to the present work, it would be interesting to analyze how well the model simulations match if naturalized stream flow values were used instead of controlled flows.

Having obtained the homogeneous zones for stream flow drought, with the knowledge of variation of drought properties within each of these regions, a mitigation plan specific to that region can be developed. This will help water resources planners overcome the gravity of water crisis in coming years.

<u>**4(b) Drought atlas for the state of Texas**</u>

Purpose and scope: The purpose of this objective is to develop drought severity-duration – frequency maps for Texas. In addition to this, maps for average annual severity, decadal variation of drought severity, and drought duration have also been prepared. This helps in visualizing the spatial variation of drought characteristics within the state of Texas.

Mean drought severity map:

Step 1: Streamflow simulations at $1/8^{th}$ degree resolution for Texas

Land surface model named VIC, which has been explained in section 2 of the first objective, will be used for obtaining daily streamflow simulations over grids of $1/8^{th}$ degree resolution over Texas. The time period of simulation is 1949-2000.

Step 2 : Classification of drought variables from the streamflow time series for each grid

Theory of runs will be used for the classification of streamflow time series into drought variables: severity and duration. The details regarding the methodology are already given in step 1 under methodology section for the first objective.

Step 3: Plotting the contour lines for annual average drought severity

From the streamflow time series for each grid, the average of annual drought severities for the years 1949-2000 was calculated for each grid. Contours were plotted based on this raster data using arcGIS. Figure 6 shows the contour map of average annual drought severity for Texas.

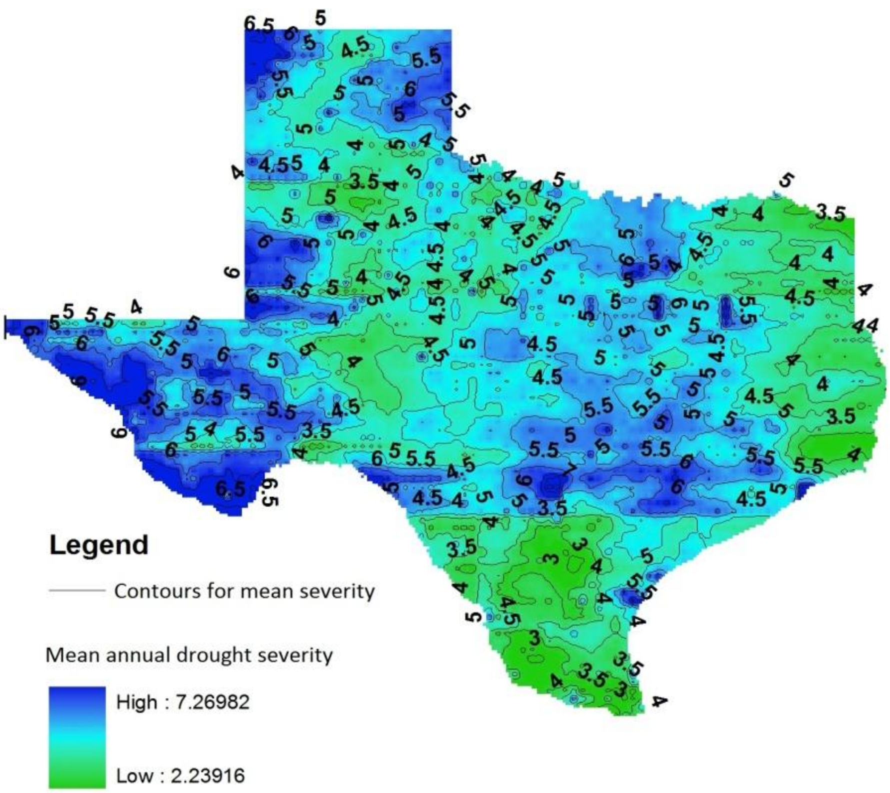


Figure 6. Contour map for average annual drought severity for Texas (1949-2000)

Observations from the map: It can be seen from the map that on an average, the severity levels were higher on the western and south eastern parts of Texas, with values ranging between 5.0-7.0. The lowest severity levels were observed over the southern and eastern parts of Texas, with values ranging between 2.0-4.0. The pattern is consistent with the precipitation pattern observed over Texas, which has a decreasing gradient from east to west.

Decadal means map for the drought severity

Following the same procedure for the mean annual drought severity map, to analyze the decadal variation of drought severity, contour maps for each decade: 1950-1959, 1960-1969, 1970-1979, 1980-1989, 1990-2000 were prepared using the annual average drought severities. Figure 7 shows decadal maps for drought severity.

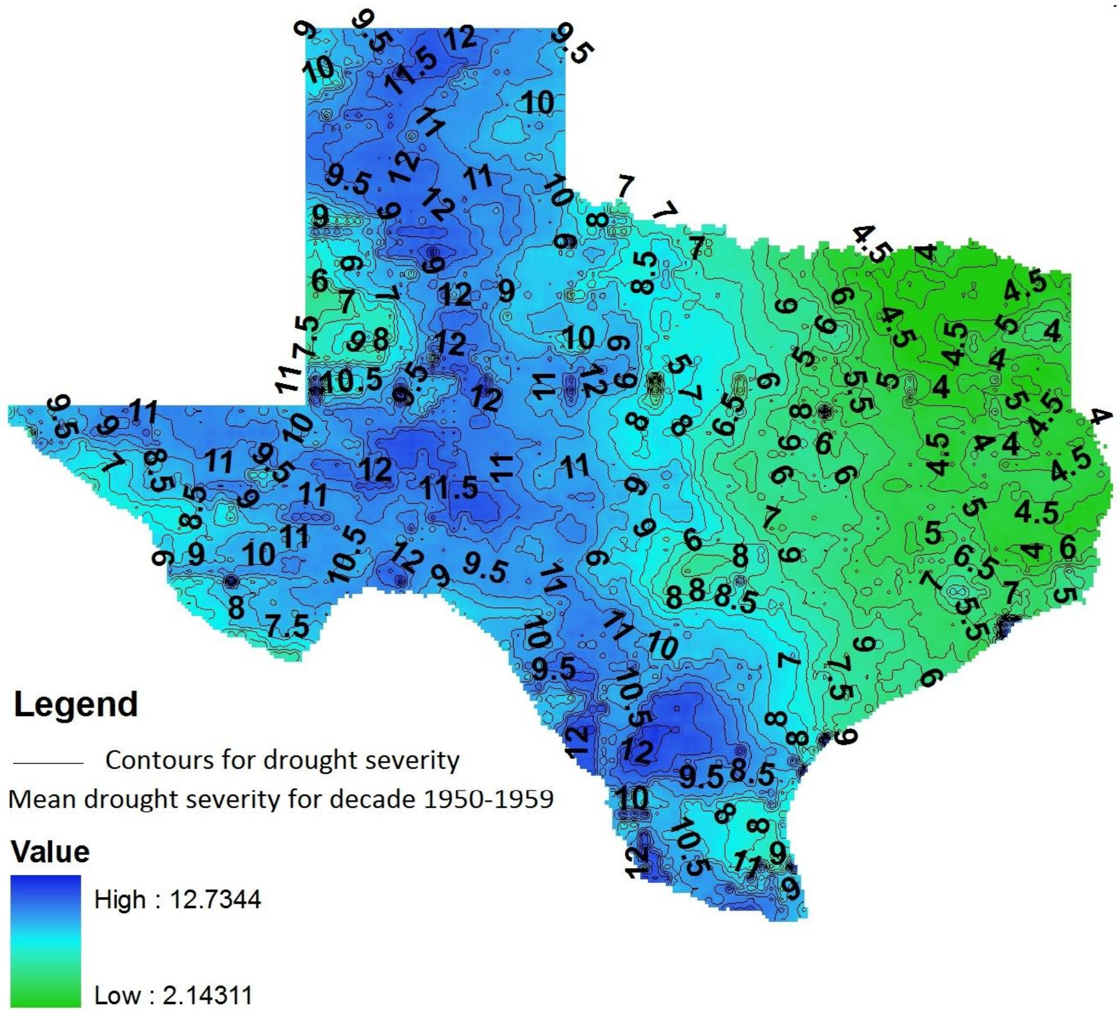


Figure 7a. Drought severity map for 1950-1959

Observations from the map: During the 1950s, the western parts of Texas showed higher severity levels in comparison to the eastern part. The 1950s show comparitively high severity levels, which might be attributed to the 1950s dust bowl.

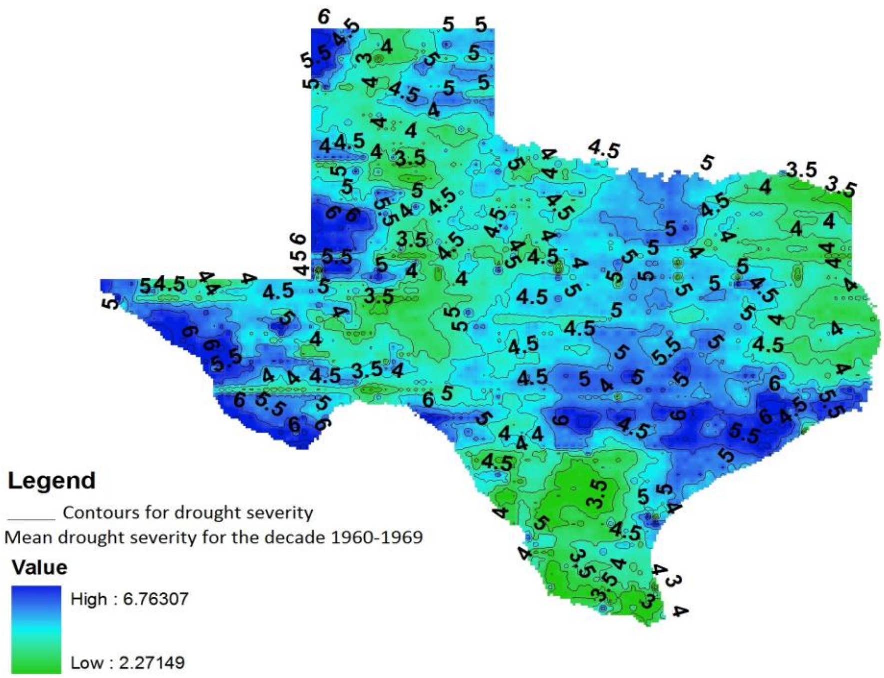


Figure 7b. Drought severity map for 1960-1969

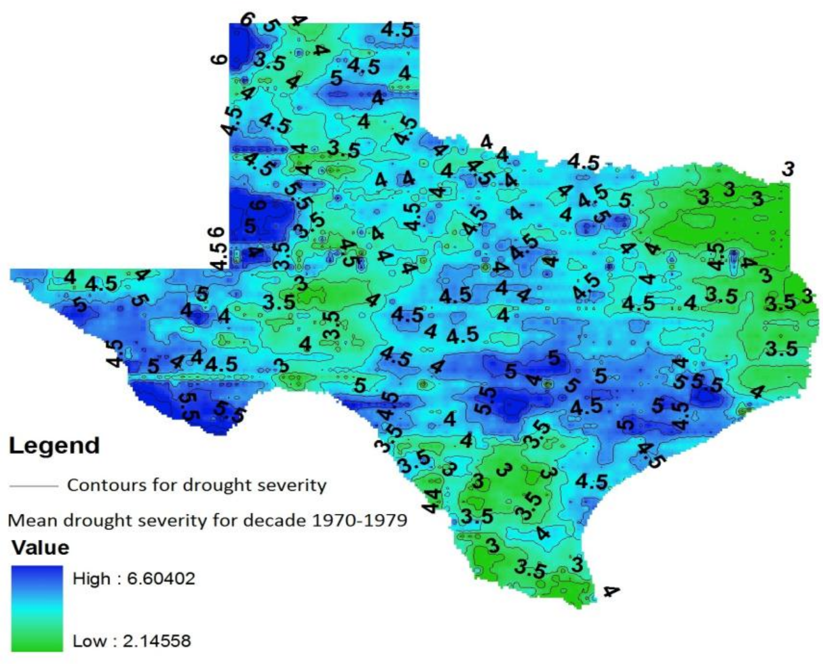


Figure 7c. Drought severity map for 1970-1979

Observations from the maps: The severity patterns were similar during the 1960s and 1970s. As compared to the 1950s, a shift in pattern can be seen wherein the severity levels have decreased along the northern, southern and central parts of Texas, and have increased towards the south eastern and eastern parts. The 1960s and 1970s have comparitively low severity levels than other decades (refer to figures below too).

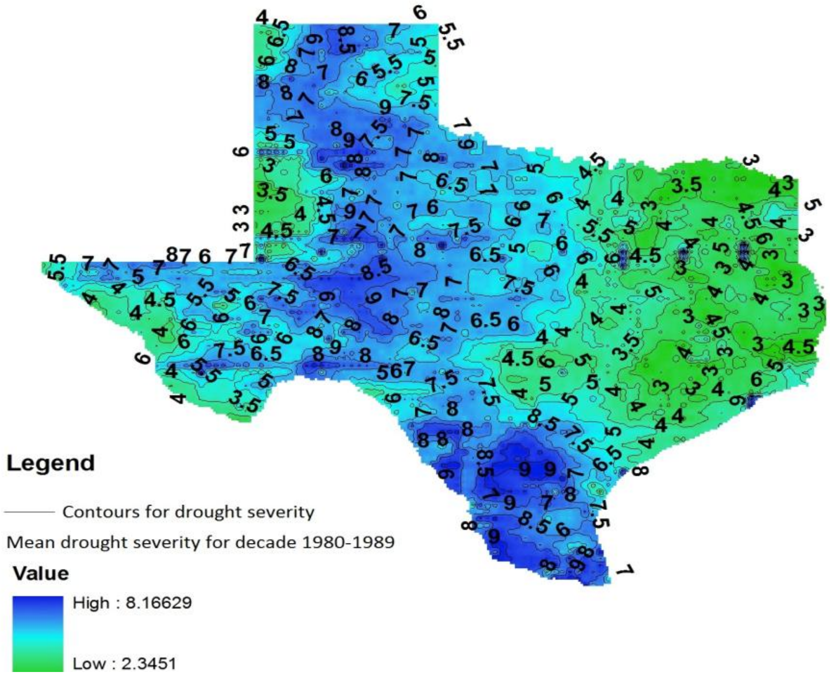


Figure 7d. Drought severity map for 1980-1989

Observations from the map: During the 1980s, the southern and central parts of Texas show an increase in severity level compared to the previous decades, whereas the southeastern parts show a decrease in severity levels. As compared to the previous decades, drought levels appear to be severe along southern Texas.

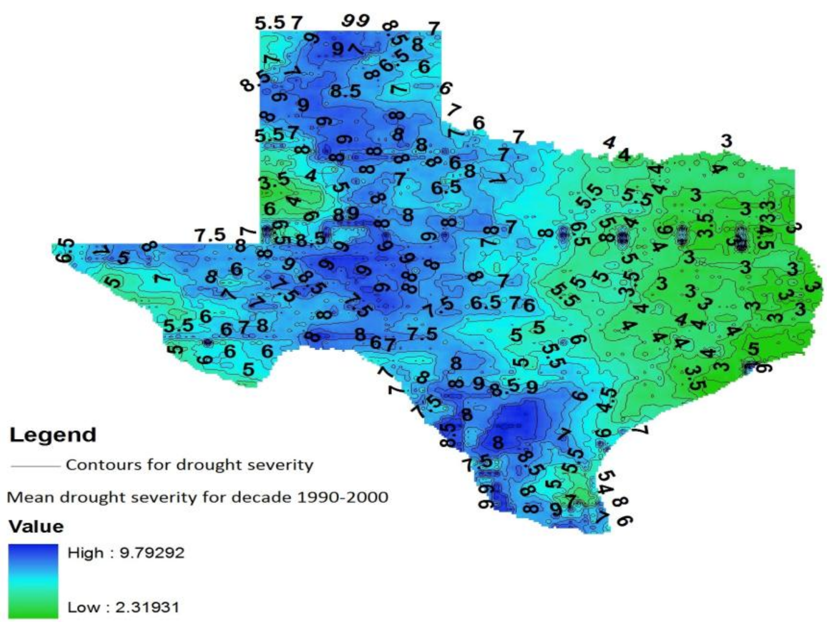


Figure 7e. Drought severity levels for 1990-2000

Observations from the map: During the 1990s, the pattern became similar to that during the 1950s, although the severity levels are not as high as the 1950s. The 1990s does show a higher severity level than the 1960s, 1970s and 1980s.

<u>Contour maps for different drought classification:</u>

It is shown in Table 1 that depending on the SSFI value, the events are classified as either wet or dry. If the index falls below -1.0, the event is considered to be dry, i.e. it indicates drought. Further, any drought event will fall under any of the following three types: moderately dry (If SSFI between -1.0 and -1.5), severely dry (If SSFI is between -1.5 and -2.0), and extremely dry (If SSFI is less than -2.0).
In this set of maps, the contour maps for moderately dry droughts, severely dry droughts and extremely dry droughts are considered on a case by case basis and plotted separately.

The steps for obtaining the drought characteristics were already explained in the beginning of the section.

Contour map for moderately dry droughts

In this case, while plotting contours, only the SSFI values that lie between -1.0 and -1.5 were considered, and the average of all such values for each grid was computed. Some of the grids might not have SSFI values lying within this specific range, and they correspond to the zero value grids in the map. Figure 8a shows the contour map for moderately dry droughts.

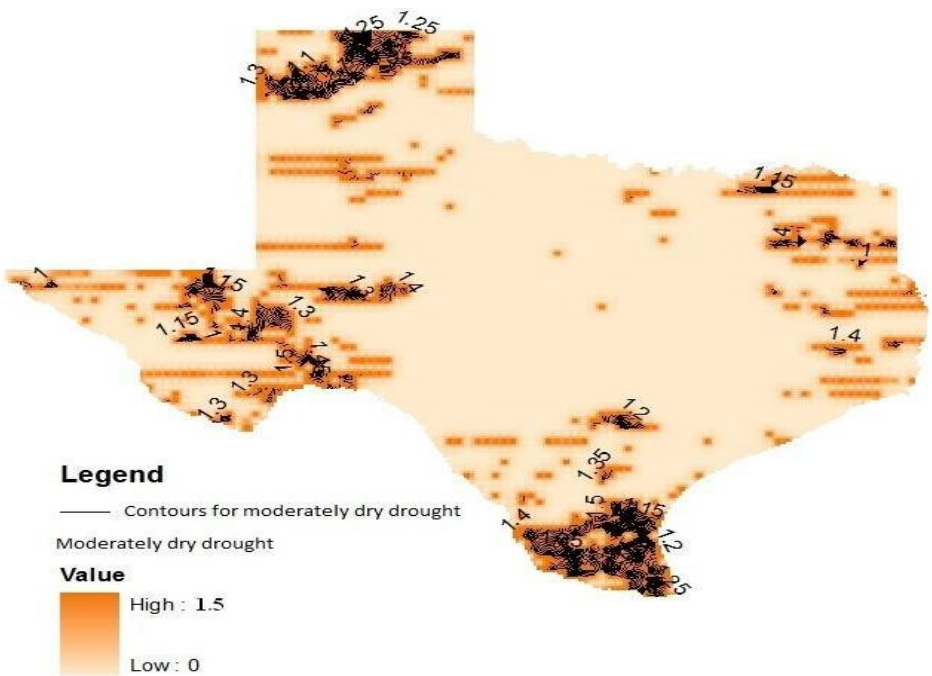


Figure 8a. Moderately dry drought within Texas

Contour map for severely dry droughts

In this case only the SSFI values lying between -1.5 and -2.0 was considered, and the rest of the values were neglected. Some grids might not have SSFI values within this specific range. Figure 8b shows the contour map for severely dry drought within Texas.

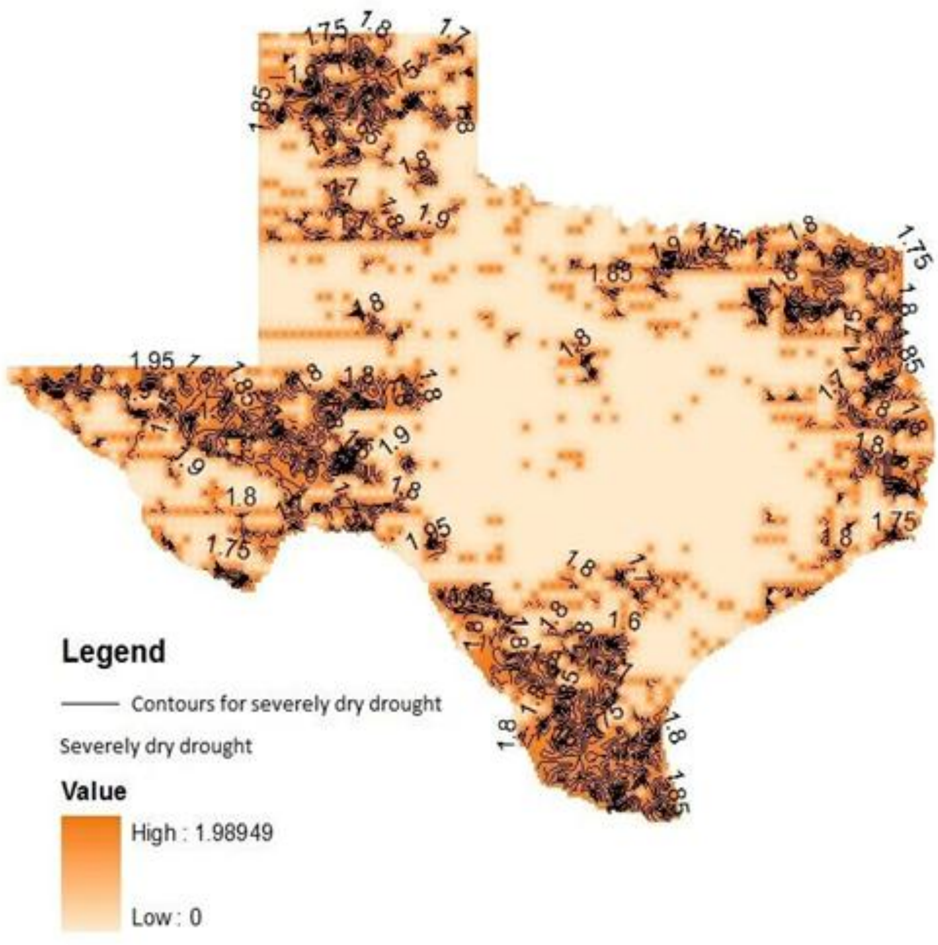


Figure 8b. Severely dry drought within Texas

Observations from the map: It can be seen that moderately dry and severely dry droughts are usually seen along the western, eastern, southern and northern tips, and not along the central parts of Texas.

Contour map for extremely dry drought

In this case, for calculating the drought severity, any SSFI value that falls below -2.0 will be considered. The annual average severity values thus calculated was used for plotting the contour map. Figure 8c shows the contour map for extremely dry drought.

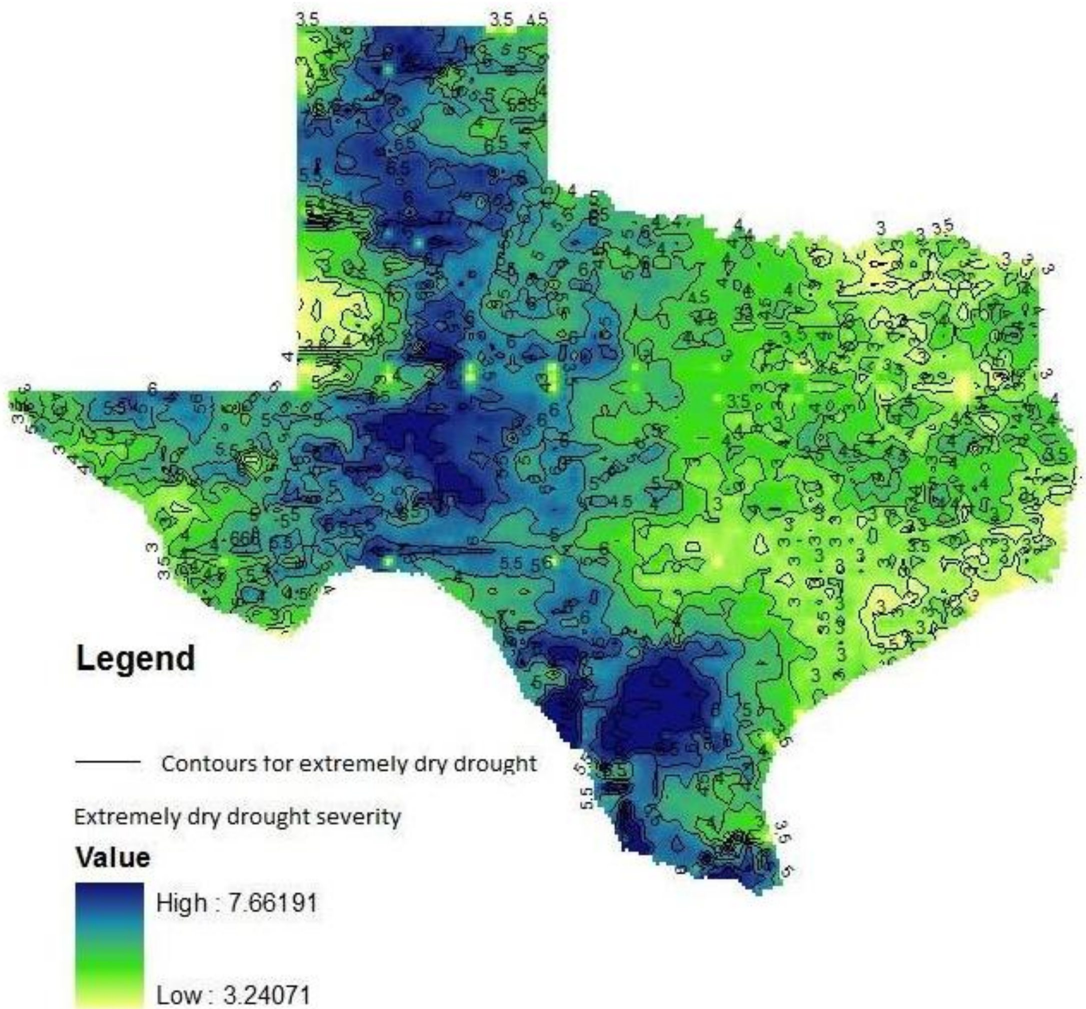


Figure 8c. Extremely dry droughts within Texas

Observations from the map: Extremely dry droughts were experienced throughout Texas during the past half century, with relatively higher levels along western, northern and southern tips.

Contours for mean duration in months for the time period 1950-2000

The drought duration represents the length of a negative run in months, i.e., it indicates how long the drought event lasts in months. Theory of runs explained in the methodology section of the first objective will be used for deriving drought durations from the VIC model streamflow simulations. Figure 9 represents the average duration of drought in months experienced by each grid over the time period 1950-2000.

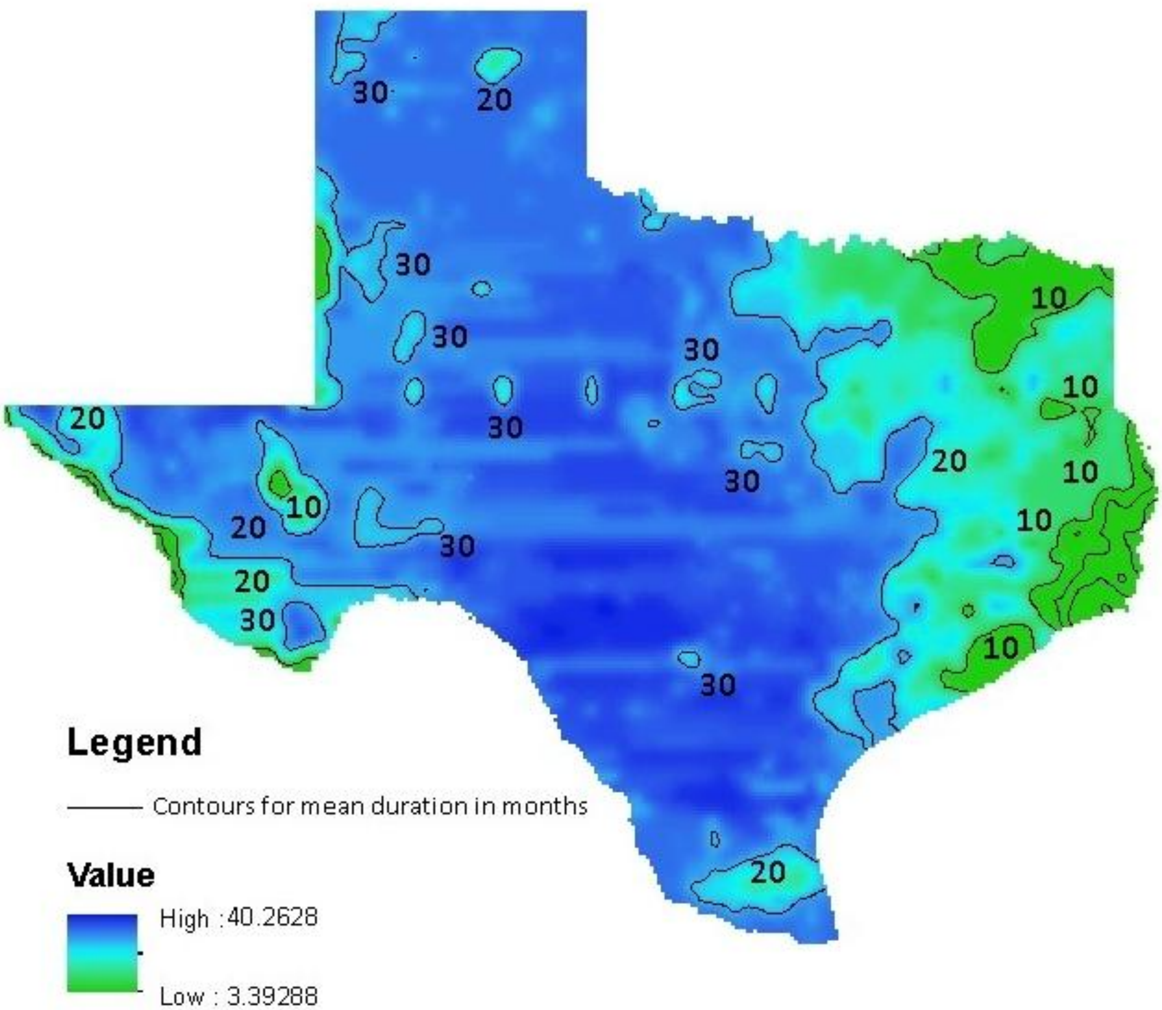


Figure 9. Average drought duration in months for each grid in Texas

Observations from the map: Relatively lower durations were seen on the western tip, and most of the eastern region. The central, western and southern parts of Texas in general show a higher incidence of drought events.

Drought severity-duration-frequency maps

Droughts are dynamic and are characterized by multiple attributes like severity, duration and magnitude (Mishra and Singh, 2010). Hence, a univariate analysis which considers each of these properties separately might not make sense. However, the derivation of bivariate distributions for drought characteristics poses problems since the marginal distributions used should belong to the same family, which might not be the case in reality since we use different distribution functions to fit different drought properties. The use of copulas to link marginal distributions to form a joint distribution was found to alleviate such problems and several studies focusing on the use of copulas in the context of drought analysis can be seen in the literature (Shiau, 2006, 2007, 2009; Kao & Govindaraju, 2010; Song & Singh, 2010a,b; Mirakbari et al.; 2010). Shiau et al. (2006, 2007, 2009) developed a methodology for drought frequency analysis and derivation of severity-duration-frequency curves using two-dimensional copulas, which will be followed to produce contour maps for drought severities for different durations and recurrence intervals.

The steps followed for preparing these maps are given below:

Step 1: Definition of drought events

For any drought event, the cumulative deficit of the variable of interest during the drought event is defined as drought severity. Drought duration is the time between the onset and the end of a drought event. The theory of runs was used for deriving drought characteristics from the stream flow time series. Details of the method are already mentioned in the report.

Step 2: Distributions of univariate drought variables

The second step will be the derivation of univariate distributions for each of the drought characteristics. Generally, drought duration is fitted as an exponential distribution (Zelenhastic and Salvai, 1987) if the drought duration is considered a continuous random variable. Gamma distribution is generally used to describe the drought severity (Zelenhastic and Salvai, 1987; Mathier *et al*., 1992; Shiau and Shen, 2001). The probability density functions of exponential distribution and gamma distribution are shown in Equations (12) and (13), respectively.

$$f_D(d) = \frac{1}{\lambda} e^{-d/\lambda} \tag{12}$$

$$f_S(s) = \frac{s^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} e^{-s/\beta} \tag{13}$$

where d>0 is the drought duration, and λ is the parameter, s>0 is the drought severity, and α, β are the shape and scale parameters, respectively. The exponential and gamma distribution parameters are derived first and separately. Given *n* independent paired observations (d_i , s_i), the log-likelihood functions for the drought duration and severity, ln $L_D(d;\ \lambda)$ and ln $L_S(s;\ \alpha,\ \beta)$, are maximized to derive the parameters.

Step 3:Copula based joint CDF for drought severity and duration

Since drought severity and duration are modeled by different CDFs, copulas are used to link the fitted models and construct the JCDF of drought severity and duration. In this study, the Clayton copula is employed to model the dependence between drought severity and duration, since it is of simple form and is commonly used in hydrology. The copula-based JCDF of drought severity and duration, therefore, become:

$$C(F_S, F_D) = (F_S^{-\theta} + F_D^{-\theta} - 1)^{-\frac{1}{\theta}}, \theta \geq 0 \tag{14}$$

where F_S and F_D are the univariate CDFs for drought severity and duration, respectively; and θ is a parameter used to measure the degree of association between F_S and F_D. The parameter of Clayton copula is estimated by the method of Inference Function for Margins (IFM) (Joe, 1997). Substituting the values of θ in Eq. (19) will give the expression for the copula based JCDF of drought severity and duration.

Step 4: Copula based drought severity-duration-frequency relationship

The relationship among drought severity, duration and frequency in terms of recurrence interval for drought events can be represented by the conditional recurrence interval which is given by (Shiau, 2007):

$$T_{S|D}(s \mid d) = \frac{1}{\gamma(1 - F_{S|D}(s \mid d))} \tag{15}$$

where *s* and *d* denote the drought severity and duration, respectively; $F_{S|D}(s|d)$ is the conditional CDF of S, given D=d, $T_{S|D}(s|d)$ is the conditional recurrence interval of S given D = d; and γ is the arrival rate of drought events which need to be fitted from the observed data.

The conditional CDF is given as:

$$F_{S|D}(s \mid d) = \frac{\partial F_{S,D}(s,d)}{\partial F_D(d)} \tag{16}$$

where $F_D(d)$ is the CDF of drought duration, and $F_{S,D}$ (s,d) is the joint CDF of drought severity and duration which will be derived using copulas as explained in step 3. The conditional distribution in eq. (16) can be rewritten as:

$$F_{S|D}(s \mid d) = \frac{\partial F_{S,D}(s,d)}{\partial F_D(d)} = \frac{\partial C(F_S(s), F_D(d))}{\partial F_D(d)} = \mathrm{C}_{F_S|F_D}(F_S(s) \mid F_D(d)) \tag{17}$$

where C is the unique copula function that links $F_S(s)$ and $F_D(d)$ to form the joint CDF. The conditional copula in terms of $F_S(s)$ and $F_D(d)$ has the following form (Joe, 1997):

$$C_{F_S|F_D}(F_S(s) \mid F_D(d)) = \left\{1 + F_D(d)^{\theta}(F_S(s)^{-\theta} - 1)\right\}^{-\frac{1}{\theta}-1} \tag{18}$$

The copula based drought SDF curve is thus given by:

$$T_{S|D}(s\,|\,d)=\frac{1}{\gamma\left[1-\left\{1+F_D(d)^{\theta}\left(F_S(s)^{-\theta}-1\right)\right\}^{-\frac{1}{\theta}-1}\right]} \tag{19}$$

This theoretical drought SDF relationship can be used to construct the dependence between drought severity, duration and the arrival rate of drought events.

Step 5: Plotting contour maps for drought severities corresponding to different durations and recurrence intervals

For selected recurrence intervals of 10, 25, 50 and 100 years, drought severity quantiles for specific drought durations can be obtained for each of the grids. This raster data will then be used for plotting the contour maps using arcGIS. Figures 10 (a to h) show the drought severity maps for drought durations of 6 and 12 months for recurrence intervals of 10, 25, 50 and 100 years.

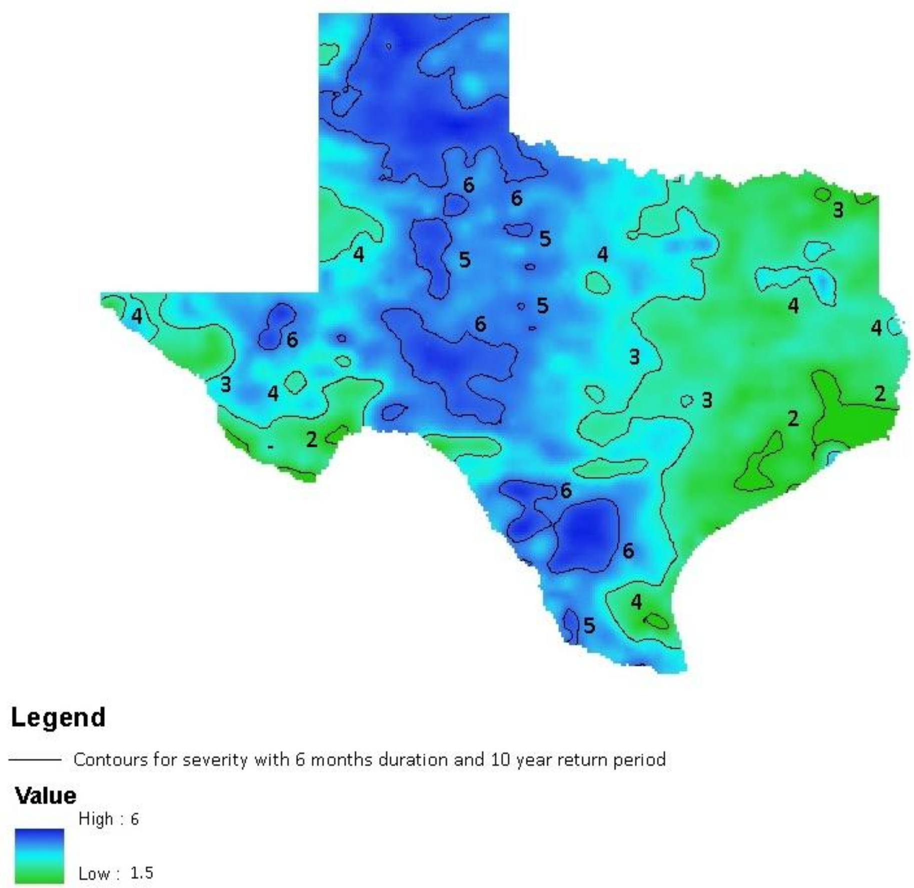


Figure 10a. Drought severity with 6 months duration and 10 year return period

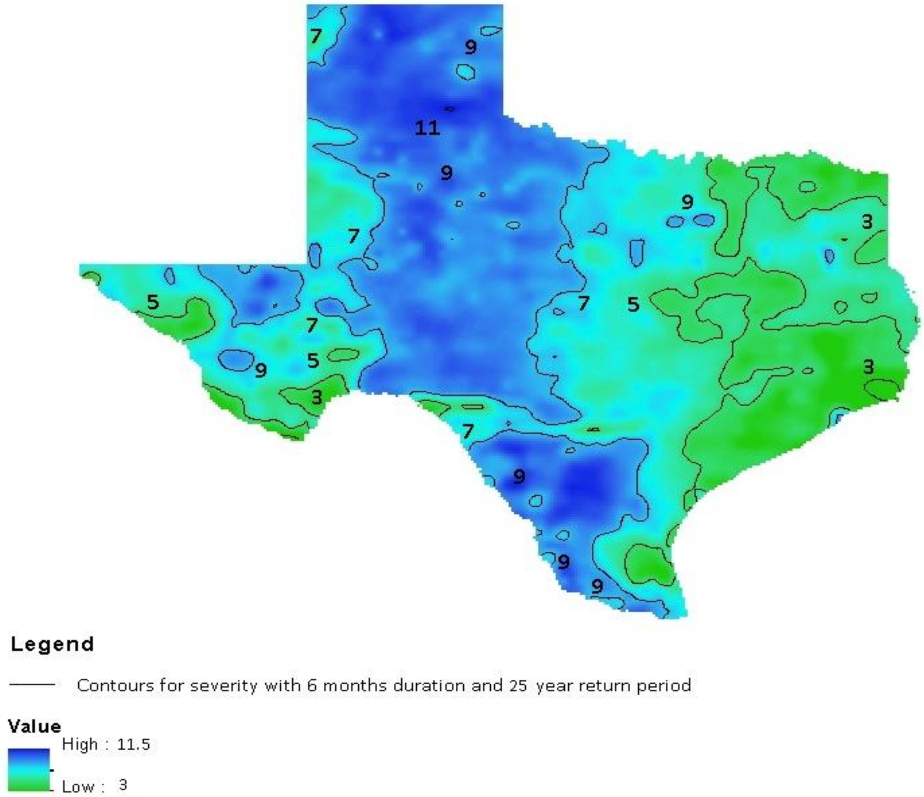


Figure 10b. Drought severity with 6 months duration and 25 year return period

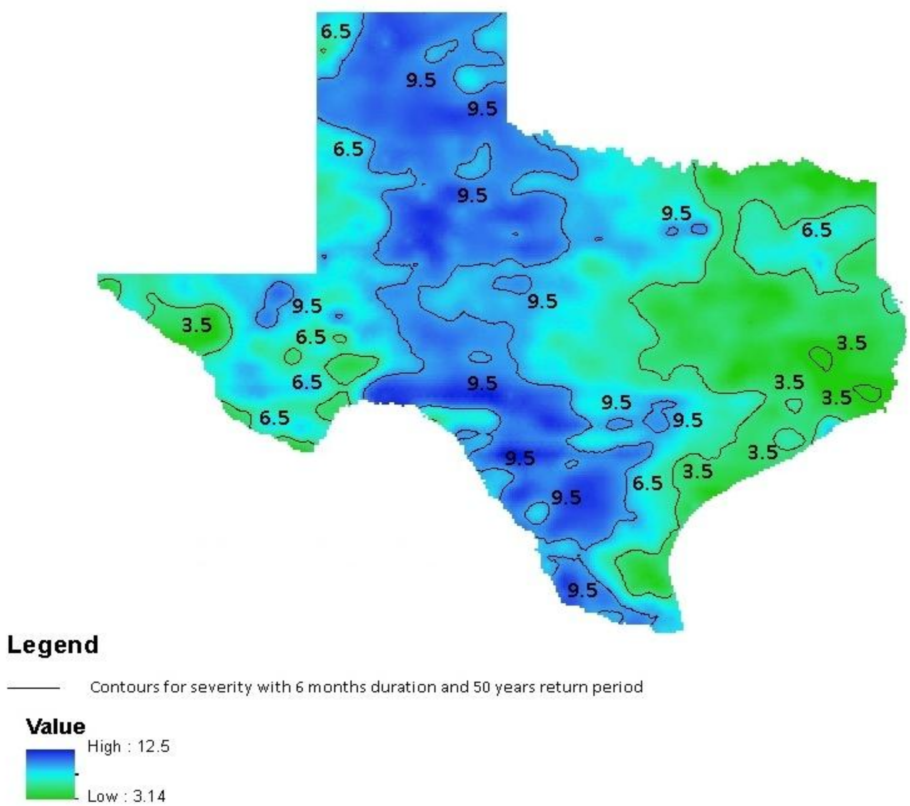


Figure 10c. Drought severity with 6 months duration and 50 years return period

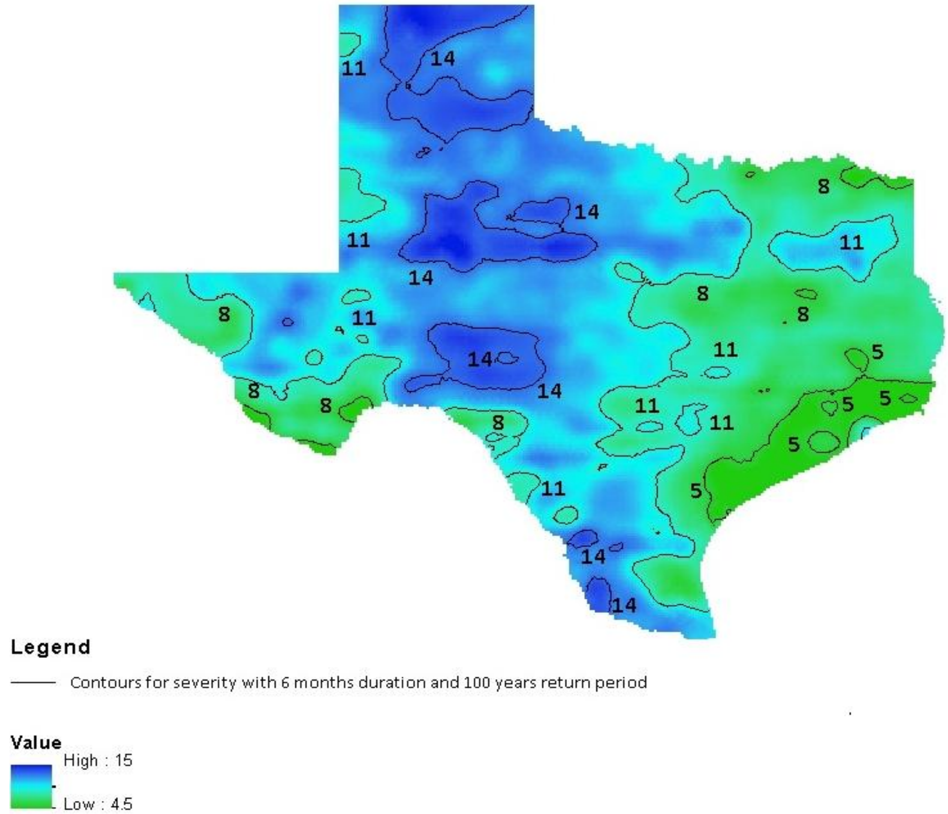


Figure 11d. Drought severity with 6 months duration and 100 years return period

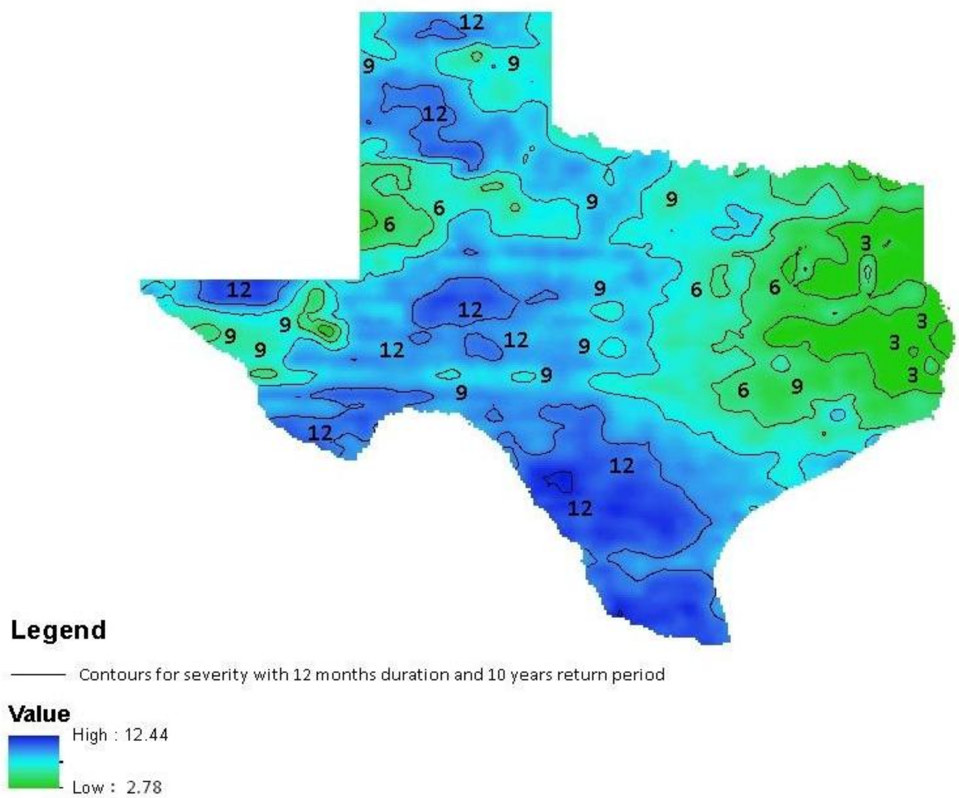


Figure 11e. Drought severity with 12 months duration and 10 years return period

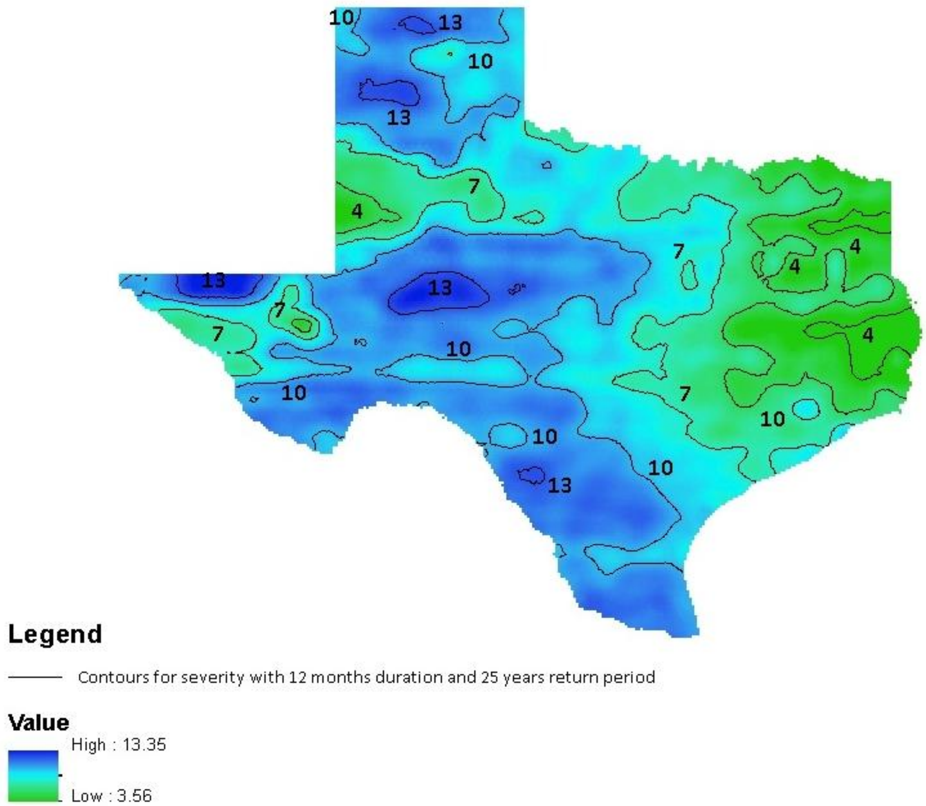


Figure 11f. Drought severity with 12 months duration and 25 years return period

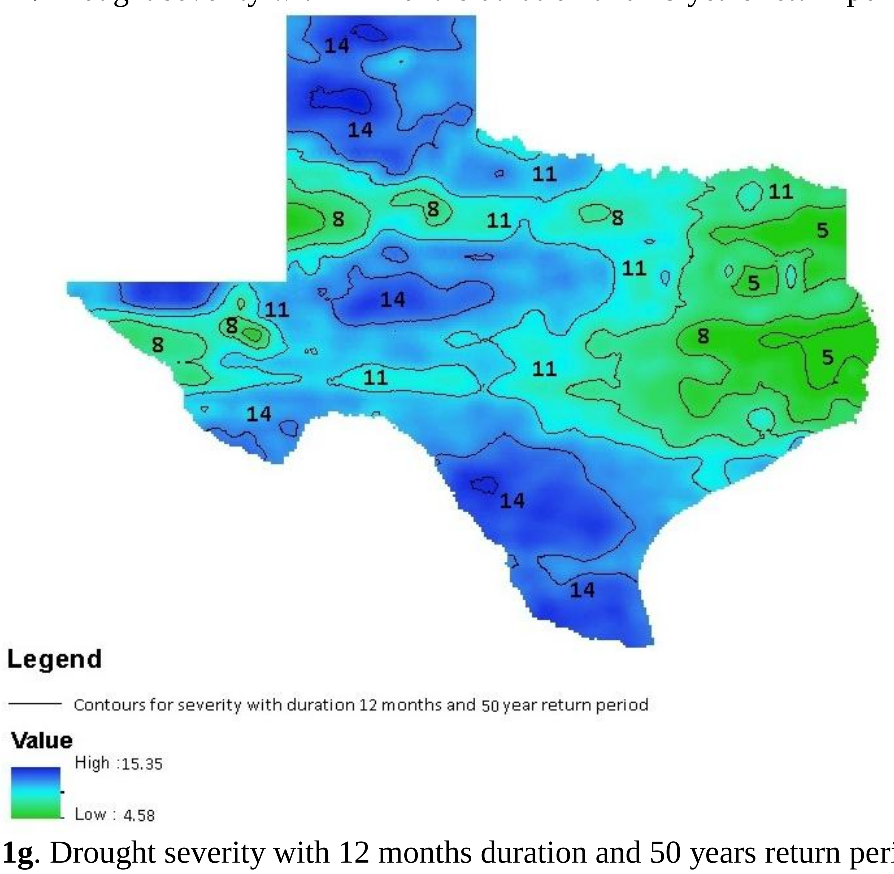


Figure 11g. Drought severity with 12 months duration and 50 years return period

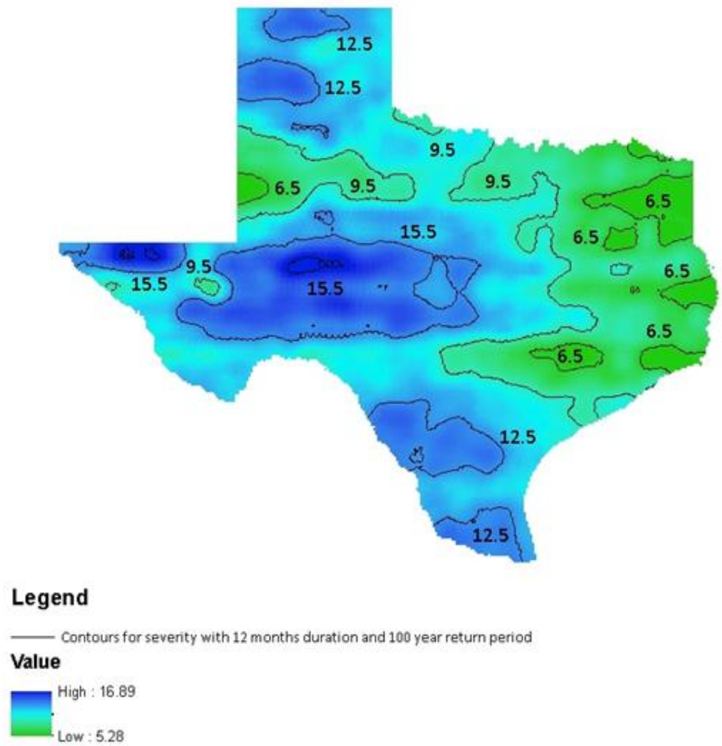


Figure 11h. Drought severity with 12 months duration and 100 year return period

Observations from the maps:

1. The drought severity varies systematically for different durations and return periods, with maximum severities along western, northern and south western Texas, which gradually decreases towards eastern Texas.
2. 6-month duration 10-year return period droughts have severities ranging from 1.5 along eastern Texas to 6 along western, northern and central Texas, whereas for 100 year return period droughts with 6 months duration, the severities range from 4.5 along eastern and south eastern Texas to 15 along the northern and south western parts.
3. 12-month duration 10-year return period droughts have severities ranging from 2.78 along eastern Texas to 12.44 along western and south western parts, whereas for 100 year return period droughts with 12 months duration, the severities range from 5.3 along eastern Texas to 16 along the central part.
4. In general, the severity-duration-frequency relationship shows a concave down pattern, i.e. the drought severity increases rapidly if the drought duration is short. As the drought duration increases, the drought severity also increases but the rate at which it severity increases will become lesser for longer drought durations.

4(c) Simulating hydrological drought properties at different spatial units based on wavelet-Bayesian regression approach

Methodology used in the study

Palmer Hydrological Drought Index (PHDI)

This is a hydrological drought index used to assess long-term moisture supply. The monthly time series generated indicates the severity of a wet or dry spell based on the balance between moisture supply and demand. The PHDI is suitable to quantify the hydrological impacts of droughts (e.g., reservoir levels, groundwater levels, etc.) which take longer to develop and it takes longer to recover from them (Palmer, 1965).

The PHDI generally ranges from - 6 to +6, with negative values denoting dry spells and positive values indicating wet spells. In the present study, we have taken different thresholds for identifying severity levels of different droughts, i.e., PHDI values less than 0 include all types of drought; PHDI less that -1 includes a range of drought from mild drought to extreme drought; PHDI values less than -2 includes moderate drought to extreme drought; PHDI values less than -3 represents severe drought and extreme droughts and PHDI less than -4 represents extreme droughts.

Bayesian linear regression

The description of the Bayesian regression model is summarized from Hoff (2009). Regression modeling describes the sampling distribution of dependent variable *y* varies with another variable or sets of independent variable $x = (x_1, \ldots, xp)$.

$$y_i = \beta^T x_i + \varepsilon_i, \quad \text{where } \varepsilon_i \sim i.i.d.\ normal\ (0, \sigma^2) \tag{20}$$

Where, β^T represents the vector of coefficients associated with a row vector of independent variables x_i and ε is *i.i.d* random normal term with mean zero and standard deviation σ.

Continuous wavelet transform

A continuous wavelet transform (CWT) decomposes a PHDI time series into wavelets and produces coefficients at a given scale. CWT's basis functions are scaled and shifted versions of the time-localized mother wavelet. A Morlet wavelet is one of the many wavelet functions which has a zero mean and is localized in both frequency and time. It provides a good balance between time and frequency localizations and is therefore preferred for application. It can be represented as (Grinsted et al., 2004):

$$\psi(\eta) = \pi^{-1/4} e^{i\omega\eta - 0.5\eta^2} \tag{21}$$

where ω is the dimensionless frequency, and η is the dimensionless time parameter. The wavelet is stretched in time (*t*) by varying its scale (*s*), so that $\eta = s/t$. When using wavelets for feature extraction purposes, the Morlet wavelet [with ω = 6] is a good choice, since it satisfies the admissibility condition (Farge, 1992; Torrence and Compo, 1998). For a given wavelet $\psi_0(\eta)$, it is assumed that X_j is a time series of length *N* [X_j, i=1, …, *N]* with equal time spacing δt. The continuous wavelet transform of a discrete sequence X_j is defined as convolution of X_j with the scaled and translated wavelet, $\psi_0(\eta)$:

$$W_n^X(s) = \sum_{j=1}^{N} X_j \psi^* \left[\frac{(j-n)\delta t}{s} \right] \quad (22)$$

CWT decomposes PHDI time series into time-frequency space, enabling the identification of both the dominant modes of variability and how those modes vary with time.

Goodness-of-fit test

To compare the observed and simulated drought time series, the goodness-of-fit was calculated based on correlation coefficient, root mean square error and mean bias error. If O_i and S_i represent observed and simulated drought time series, then:

Correlation coefficient (CC): $$\frac{n\sum O_i S_i - (\sum O_i)(\sum S_i)}{\sqrt{n(\sum O_i^2) - (\sum O_i)^2}\sqrt{n(\sum S_i^2) - (\sum S_i)^2}} \quad (24)$$

If $e_i = O_i - S_i$ denoted as individual model-prediction errors, then model performances are based on statistical summaries of e_i (*i=1, 2, 3,…,n*):

Root mean square error (RMSE): $$\left[\frac{1}{n} \sum_{i=1}^{n} |e_i|^2 \right]^{1/2} \quad (25)$$

Mean bias error (MBE): $$\frac{1}{n} \sum_{i=1}^{n} e_i \quad (26)$$

Study area and data used

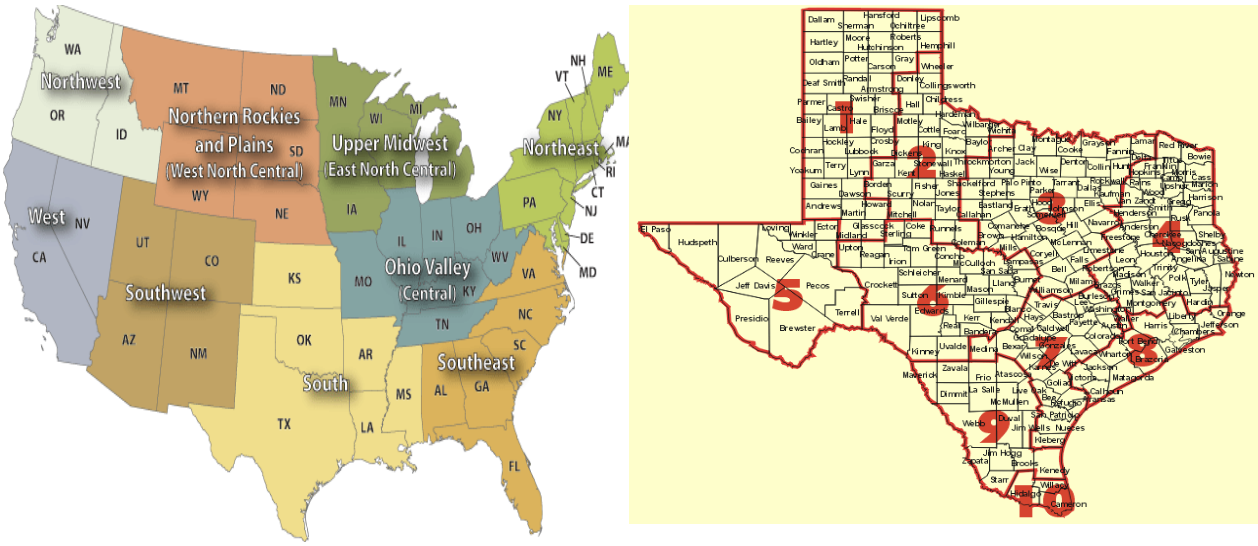
Different spatial units were chosen to test the potential of precipitation and temperature to simulate hydrological drought using PHDI. The definition of spatial units used in this paper is based on the following notion: (a) climatic division is the smallest unit used in this study, (b) the state (say Texas) is combination of several climatic divisions (units), and (c) the regional unit is combination of several states. The spatial units include (see table 1 and figure 12): all climatic division (1 to 10) of the state of Texas, state of Texas, different regions of USA (Northeast, East North Central, Central, Southeast, West North Central, South, Southwest, Northwest and West regions). Monthly precipitation, temperature and PHDI values which are available from 1900 to 2000 were retrieved from National Climatic Data Center of National Oceanic and Atmospheric Administration (NOAA). For both precipitation and temperature, monthly averages within a climatic division have been calculated by giving equal weight to stations. To adjust the climatic division averages, the model described by Karl, et al. (1986) was used such that all stations end their climatological day at midnight; i.e., climatological day coincides with calendar day.

Statistical properties of precipitation across different spatial units are shown in Table 13. Precipitation in state of Texas is not evenly distributed and the mean annual precipitation distribution correlates roughly with longitude and varies little from north to south. The maximum mean annual precipitation was observed for climatic division 8 (121cm) and climatic division 4 (118cm) located in the far eastern part of Texas, whereas the minimum was observed in climatic division 5 (32 cm) located in the far western part of Texas. A higher amount of standard deviation was observed in the region witnessing a higher amount of precipitation, for example climatic divisions 8 and 7.

Based on the regional unit, the maximum mean annual precipitation was observed to be higher in southeast region (128cm) followed by the central region (108cm) and northeast region (104cm), whereas the minimum was observed in southwest region (34 cm) followed by west and west north central region (43cm). The standard deviation pattern witnesses higher values with higher mean annual precipitation, however the variation was noticed in lower amounts of annual precipitation. The west north central and west region observe the same amount of mean annual rainfall (42cm) considered to be among the lowest values, however they witness different standard deviations of 5.5 and 11 cm, respectively. Positive kurtosis and skewness are observed in the maximum number of selected spatial units.

Table 13. Spatial units and statistical properties of their annual precipitation for the period of 1900-2000.

Sl. No	Spatial location	Mean (cm)	Standard Deviation (cm)	Kurtosis	Skewness
1	Climatic division 1 (Texas)	47.92	10.63	5.88	0.71
2	Climatic division 2 (Texas)	59.85	13.53	4.32	0.45
3	Climatic division 3 (Texas)	87.23	17.58	2.58	-0.01
4	Climatic division 4 (Texas)	118.30	22.00	2.54	0.31
5	Climatic division 5 (Texas)	31.58	9.24	4.81	0.85
6	Climatic division 6 (Texas)	64.54	16.94	3.05	0.44
7	Climatic division 7 (Texas)	88.30	21.25	2.49	0.13
8	Climatic division 8 (Texas)	121.18	26.55	2.67	0.38
9	Climatic division 9 (Texas)	58.96	14.34	2.54	0.30
10	Climatic division 10 (Texas)	63.58	14.47	3.59	0.60
11	State of Texas	71.19	13.43	2.92	0.15
12	North east region (USA)	104.35	10.12	3.66	0.39
13	East north central region (USA)	75.63	8.56	2.91	-0.30
14	Central region (USA)	107.79	11.68	2.88	-0.09
15	South east region (USA)	127.71	13.56	2.45	0.07
16	West north central region (USA)	42.99	5.50	3.13	0.13
17	South region (USA)	90.02	12.41	2.91	-0.08
18	South west region (USA)	34.36	5.70	4.09	0.35
19	North west region (USA)	68.37	9.65	2.63	0.21
20	West region (USA)	42.82	10.95	3.69	0.87



(a) **(b)**

Figure 12. (a) Nine climatically consistent regions within the contiguous United States identified by National Climatic Data Center (Karl and Koss, 1984), (b) Ten climate division located within the state of Texas.

Results and Discussion

Comparison of drought properties among spatial units

Good correlation was observed among neighboring climatic divisions (Figure 13), for example the PHDI time series in climatic division 1 had a correlation strength of 0.84 (climatic division 2) and 0.71 (climatic division 5) which happen to be neighboring climatic divisions. This suggests that droughts are regional in nature for most parts of Texas. Therefore, the drought causing variables are likely to share similar association at a regional scale. The PHDI time series for the whole of Texas shares a stronger correlation coefficient (>0.74) with all climatic divisions except climate division 10 with a correlation coefficient of 0.6. The PHDI time series for larger spatial units beyond Texas, i.e., south region of USA which includes many states (TX, OK, KS, AR, LA and MS) shares a good correlation with climatic divisions of Texas except climatic divisions of 5, 9 and 10. It is worth noting that the correlation strength remains strong among climatic divisions, state and at region. However, no correlations were observed at higher spatial units which comprise multi states from different parts of the USA.

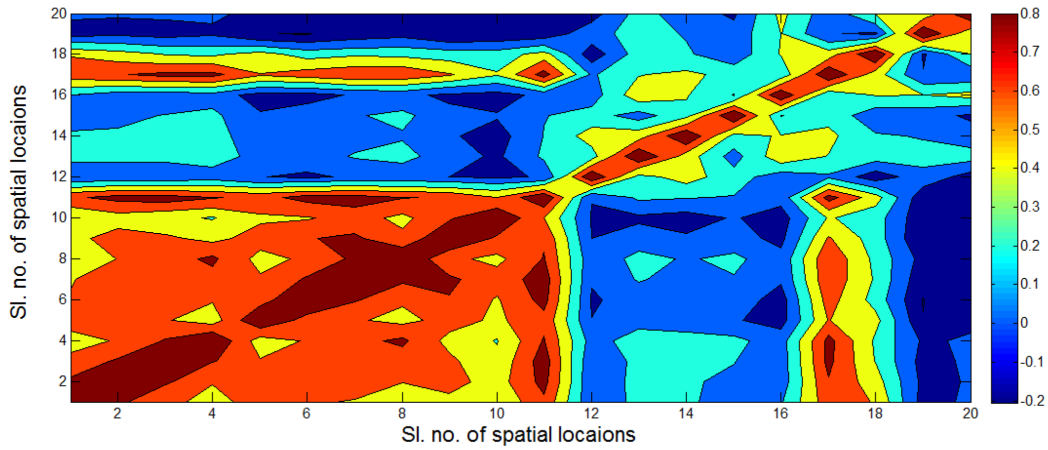


Figure 13. Linear correlation strength among spatial locations.

The number of droughts, maximum drought severity, and maximum drought duration were compared among spatial units. In this case all the droughts were considered for which the PHDI was consecutively less than -1. Based on this criterion the number of droughts that occurred among climate divisions of Texas included: climatic division 1 (61), climatic division 2 (58), climatic division 3 (49), climatic division 4 (65), climatic division 5 (60), climatic division 6 (51), climatic division 7 (50), climatic division 8 (60), climatic division 9 (65), climatic division 10 (58) and whole of Texas (45). Among the climatic divisions the number of droughts did not follow any pattern, as the maximum number occurred in all parts of Texas. The lowest number of droughts generally occurred in the sub-tropical semi-humid climate. Another interesting fact was found to be number of droughts based on the state of Texas was less in comparison to any climatic division within the state of Texas. The number of droughts at a regional unit found to be maximum in the regions located in Northeast, South east and Northwest region of the USA. The minimum number of droughts occurred in west north central region of the USA which happens to be the lowest among all the spatial selected regions.

After knowing the number of drought events, it will be good to look at the maximum drought duration and severity in different spatial units [Figure 14]. Based on number of drought events, maximum duration and maximum severity, different spatial units were compared. Important observations include: (a) the lowest number of drought events occurred in west north central region which happens to have witnessed the maximum drought severity and maximum drought duration (99 months). Therefore chances of getting longer duration drought are higher for this region. (b) The maximum number of drought events occurring in the regions (southeast and northwest regions) lies within the first five positions in terms of lowest drought duration or severity in comparison to all other spatial units. (c) The strong correlation coefficient was observed between maximum duration and maximum severity whereas the same is not true based on the number of events.

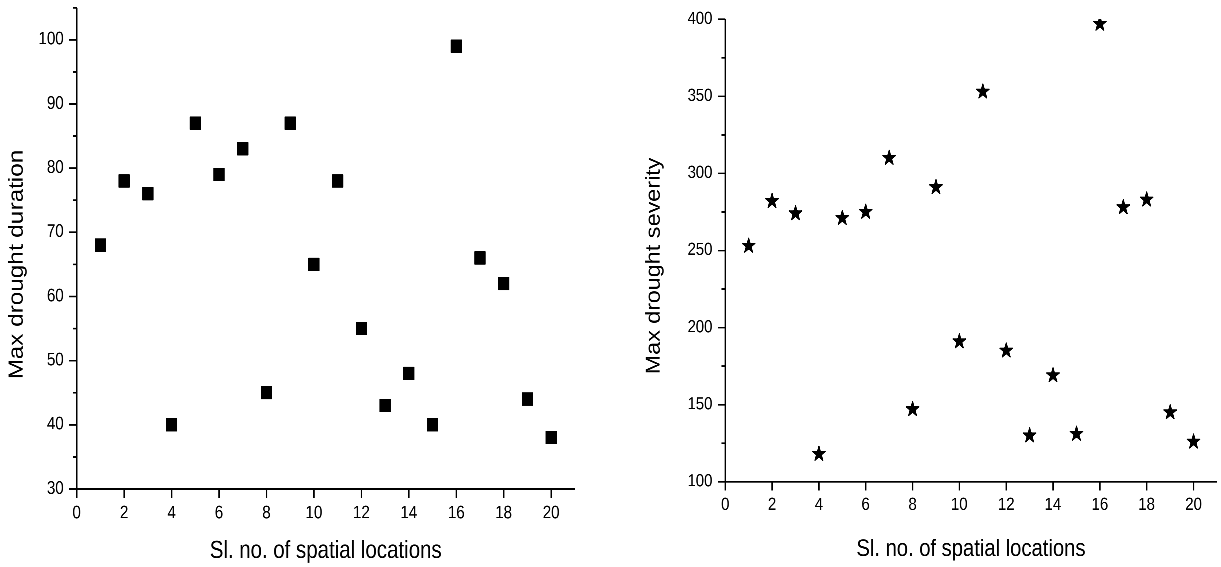


Figure 14. Plot of maximum duration and severity that occurred in the selected spatial units during the period of 1900 to 2000.

Comparison between wavelet Bayesian regression and Bayesian regression model

The wavelet Bayesian regression model depends on the decomposed PHDI time series and therefore the selection of number of bands which carry significant power is important for model setup. The spectral bands were obtained according to average wavelet spectra of PHDI. In the current discussion the PHDI time series for all spatial units can be separated into 6 significant bands so that the lower bands (first and second) show the noisy data, while the upper bands (fourth, fifth and sixth) stand for low frequency variation of PHDI. All the bands carry specific information related to original time series, for example, the higher level bands contain only information on long time cycles of the concerned variable and exclude other properties, such as noisy data, trends, whereas short times only accounts for noisy data. Therefore, predicting the homogenous (high and low frequency) time series obtained from wavelet decomposition is more stable which is its major advantage and enables the Bayesian regression models to simulate with more accuracy.

For comparison, the Bayesian regression and wavelet Bayesian regression models were applied to climatic division 1 located in Texas considering PHDI as the hydrological drought index and precipitation and temperature as meteorological variables. The length of burn-in period is 10,000 and the number of iteration was chosen as 50,000 during the sampling process of the Bayesian regression analysis. The simulation of PHDI was carried out considering 1900-1955 as training period and 1956-2000 as testing period (Figure 15).

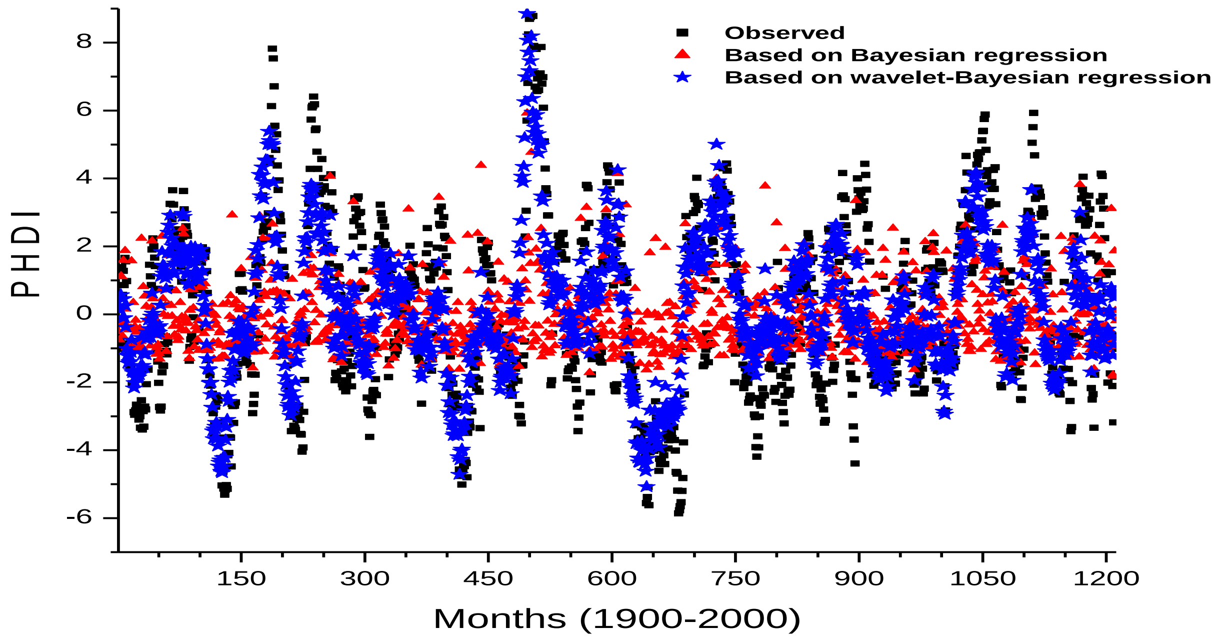


Figure 15. Training and testing of modeled PHDI time series based on Bayesian regression and a combination of wavelet Bayesian regression (Training set: 1900-1955, testing set: 1956-2000).

It was observed that the wavelet Bayesian regression approach was able to match the pattern and peaks better than the Bayesian regression approach. To further quantify the results obtained from training and testing periods, the goodness-of-fit was calculated using the correlation coefficient (CC), root mean square error (RMSE) and mean bias error (MBE). Based on CC it is 0.35 and 0.27 (Bayesian regression) and 0.78 and 0.65 (wavelet-Bayesian regression) during training and testing periods, respectively. For the Bayesian regression RMSE was 2.70 and 2.38, whereas for the wavelet-Bayesian regression it was 1.80 and 1.84 during training and testing period, respectively. Similarly, MBE was 0.07 and 0.34 for the Bayesian regression, whereas for the wavelet Bayesian regression it was -0.014 and 0.018 during training and testing periods, respectively. From these three goodness-of-fit tests it can be observed that the wavelet Bayesian regression performed better than did the Bayesian regression.

Application of wavelet Bayesian regression model to different spatial units

The Bayesian wavelet regression was applied to twenty selected spatial units and their goodness-of-fit values were calculated for comparison in terms of the predictability of hydrological droughts [Figure 16]. Hydrological droughts were simulated considering 1900-1955 as a training period and 1956-2000 as a testing period. The highest (rank 1st) CC for hydrologic drought simulation were observed with a CC value of 0.81 in Climatic division 5 (Texas) and with a CC value of 0.72 in northwest region (USA) during training and testing period respectively. However, based on the other two goodness-of-fit (RMSE and MBE), the northwest region (USA) ranked 3rd and 18th during testing period. Therefore, it is noted that all three goodness-of-fit tests rank differently in identifying the regions having better hydrological drought predictability. Based on CC the observation includes: (a) higher correlation coefficients (between 0.7 and 0.8) were observed for the climatic division in Texas for the training period, (b) during the testing period the performances were comparatively lower (CC values between 0.5 and 0.6) for climatic divisions in and including the state of Texas. The difference between the training and testing RMSE values was very small (0 to 0.04) for climatic division 1 in Texas, central region, south east and northwest regions of USA, and comparatively large (climatic division 5 and 9) in the south-western part of Texas. The variability in RMSE values did not follow a clear pattern.

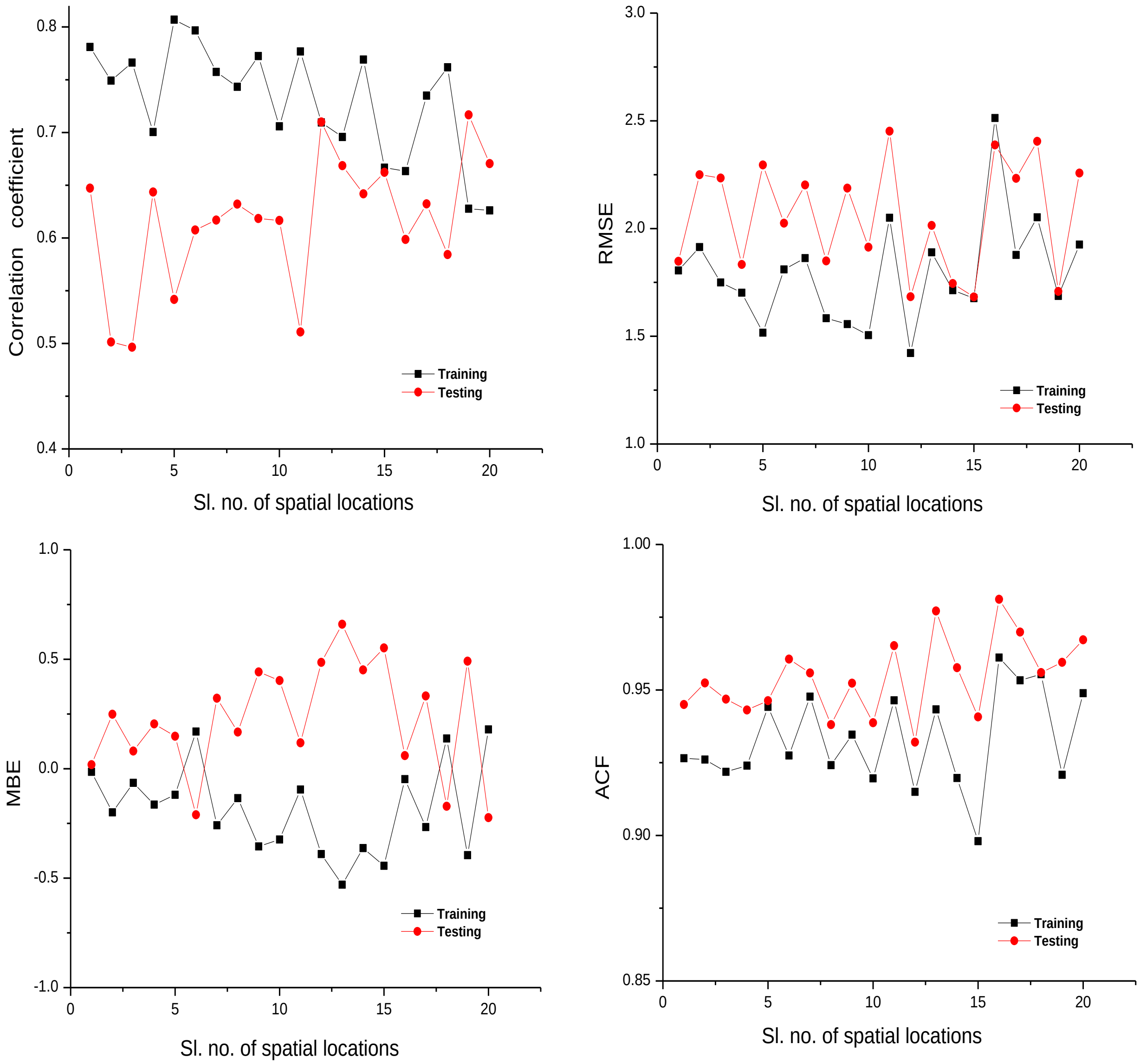


Figure 16. Comparison between training and testing PHDI time series obtained from wavelet Bayesian regression model in terms of (a) correlation coefficient, (b) root mean square error (RMSE), (C) mean bias error (MBE) and (d) lagged one autocorrelation coefficient for different spatial units.

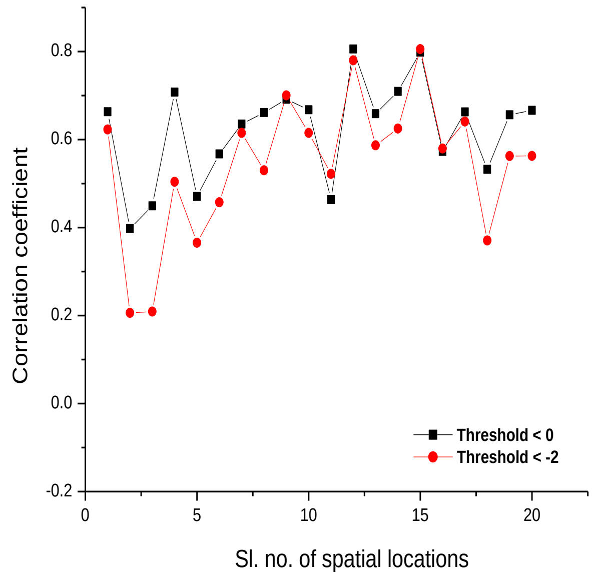
Based on MBE, a general pattern was observed in the predictability of hydrological drought using the wavelet Bayesian regression approach with a negative bias in the testing period except a few regions. Within the state of Texas, climatic divisions (9 and 10) had higher positive bias values (0.4 and 0.44), whereas at larger spatial units higher bias occurred in northeast region

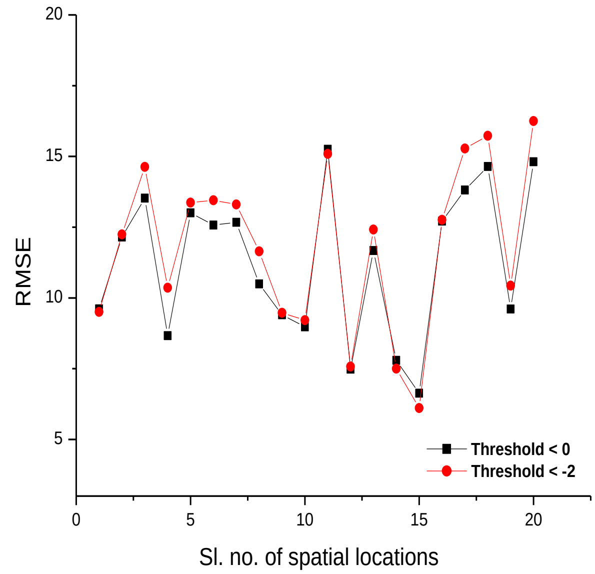
(0.48), east north central region (0.66), central region (0.45), south east region (0.55) and northwest region (0.49) of USA.

The autocorrelation coefficient (ACF) which is the correlation with its own past values can be considered as a form of persistence. The ACF was calculated for actual, training and testing time series and based on observations: (a) the PHDI time series had stronger persistence with lag 1 ACF values varying between 0.87 and 0.97; (b) the lag 1 ACF obtained from the simulated time series was higher than that from the actual time series, leading to higher persistence in the time series.

After quantifying the simulated PHDI time series, it will be appropriate to compare the annual drought characteristics (severity and duration). As was observed in the previous section the wavelet Bayesian regression performed better in capturing peaks, therefore two thresholds (0 and -2) were chosen to further analyze the relationship between observed and simulated annual drought duration and severity. In general the performance for annual drought severity based on the zero thresholds was slightly higher than that with -2 threshold in most of the regions (Figure 17). Interesting patterns were observed based on the comparison of annual drought severity correlation coefficient: (a) the pattern for annual drought severity differed from that of PHDI time series; (b) based on the two threshold levels, lower performances were observed for climatic divisions 2, 3, and 5; (c) better performances were observed for climatic divisions 4 and 9 based on the zero threshold level, however the performance of climatic division 4 reduced significantly when threshold level increased to -2; (d) for the larger spatial units better performances were observed for northeast and south east regions and poor performance was observed for southwest region. The performance measured for simulated annual drought severity based on RMSE seemed to be poor when compared with the RMSE for the simulated PHDI time series.

Similarly, the performance based on MBE was poor for annual drought severity except for the spatial units of northeast, east north central, central, southeast and northwest regions. The positive biases were observed in most of the spatial units with maximum values in the southwest and west regions. This clearly explains that the positive bias values were due to the lower simulated values of annual drought severity with respect to the actual values. Based on the goodness-of-fit, comparison between observed and simulated annual drought durations at two threshold levels for selected spatial units are shown in Figure 18.





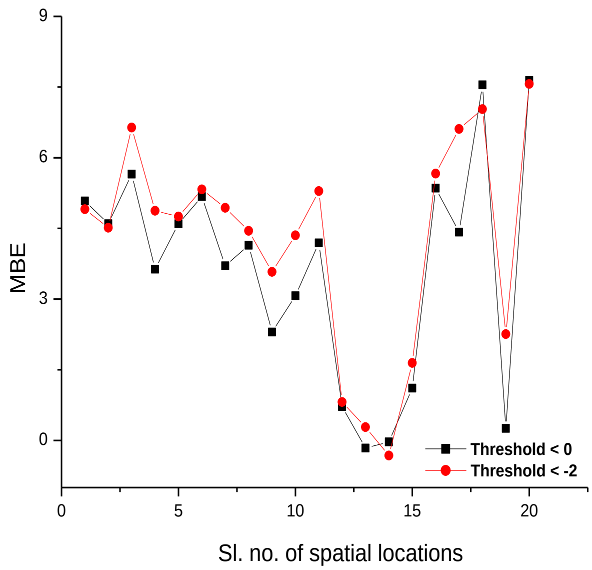
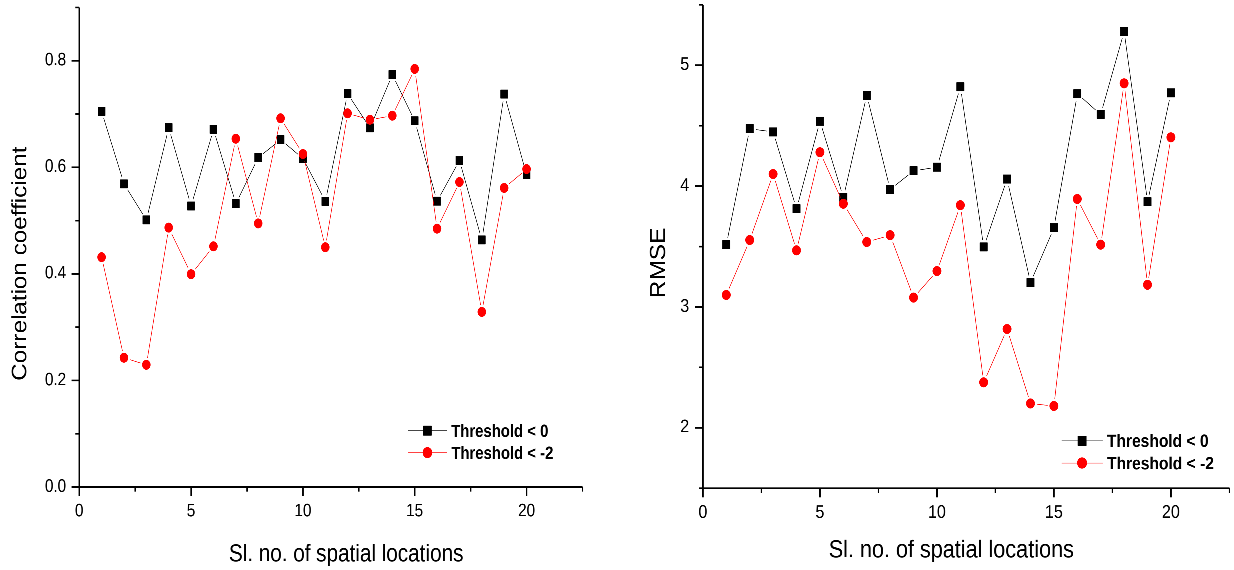


Figure 17. Comparison between observed and simulated annual drought severity at two threshold levels for selected spatial units (simulated period: 1956-2000).



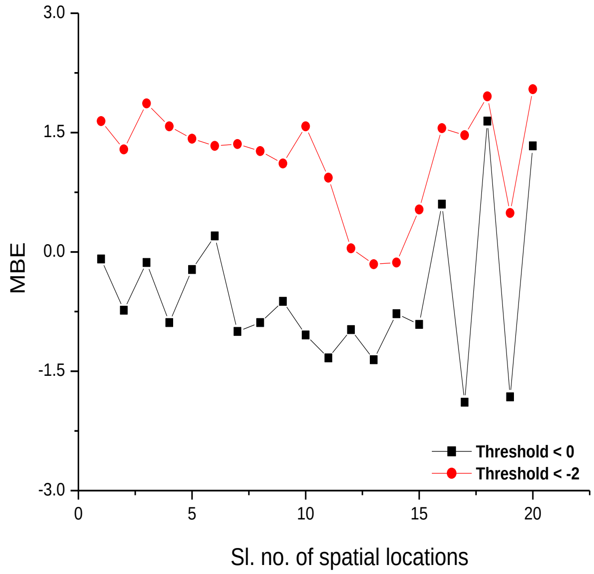


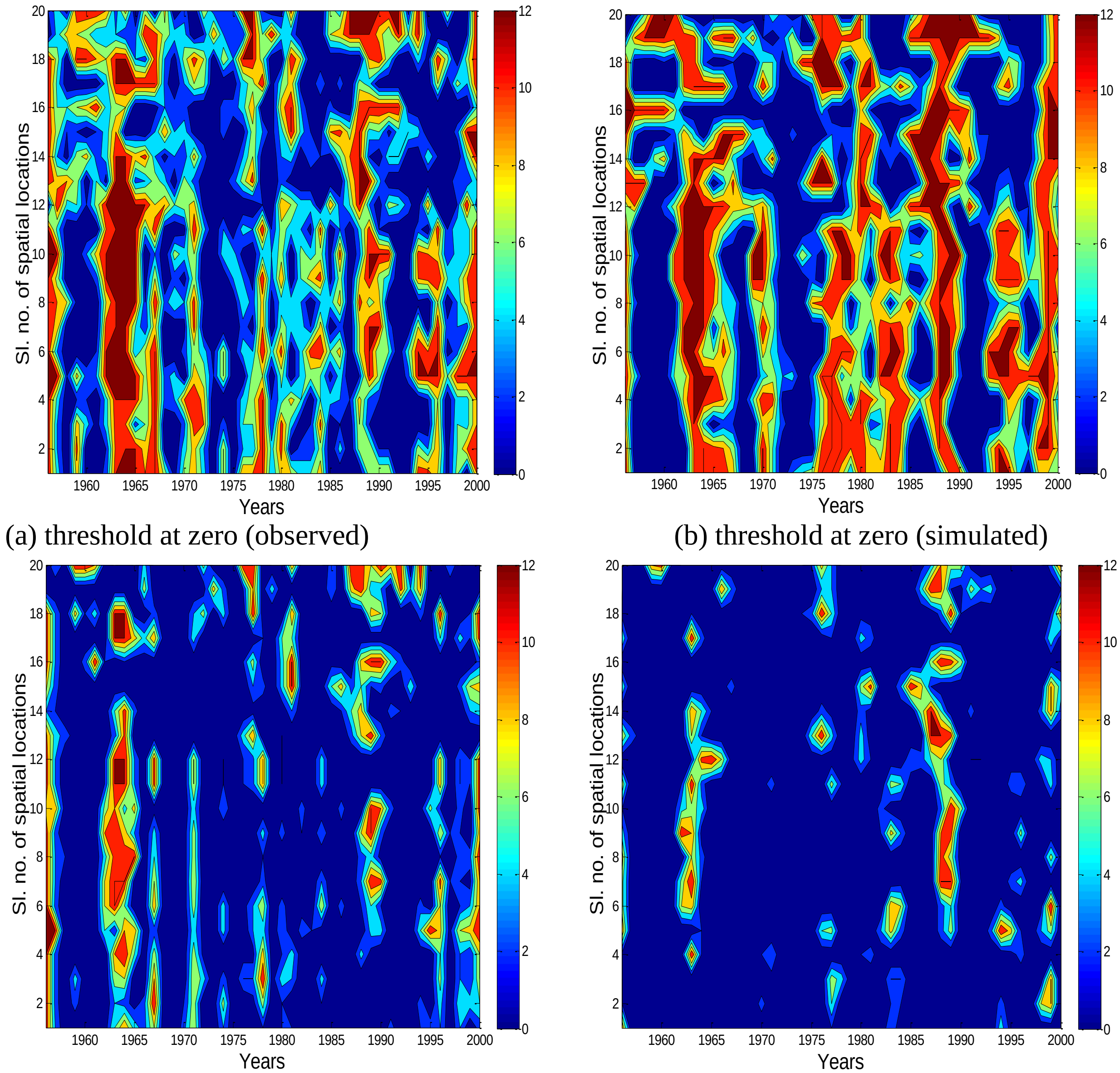
Figure 18. Comparison between observed and simulated annual drought duration at two threshold levels for selected spatial units (simulated period: 1956-2000).

The CC based on the zero threshold was higher than the minus two threshold level, with the higher difference observed for climatic divisions (1-5) located in Texas. The better performance during the testing period based on the CC values occurring in decreasing order up to first three regions included central region, northeast region, and northwest region. Higher CC values for these regions were supplemented by the lower RMSE values in most of the spatial units. An important observation was made based on MBE: (a) using the zero threshold the positive bias was noted among spatial units, (b) whereas using the minus two threshold level negative bias values were seen in 17 out of a total 20 spatial units, and (c) it is worth noting that bias varied with the type of drought time series used, with the highest values observed in annual drought severity followed by annual drought duration and the PHDI time series.

Spatio-temporal comparison based on annual drought severity and duration

The annual drought severities at two different thresholds (0 and -2) are plotted for selected spatial units as shown in Figure 19. It was observed that based on these comparison are: (a) the simulated annual drought severity could not capture the actual maximum annual drought severity, for example the maximum annual drought based on the observed PHDI time series reached about 70, whereas based on the simulated data it reached 55. (b) The simulated annual drought time series could capture the units of actual drought events, however the limitation included frequent indications of drought events in the simulated time series which did not occur in the observed time series. (c) Even though all spatial units are not affected by the drought in the observed time series, however the simulated time series indicated droughts in larger number of spatial units. (d) The performance improved when the threshold of both observed and simulated time series changed to -2, as the spatial and temporal units were more pronounced.

Comparison between observed and simulated annual drought durations for different spatio-temporal units is shown in Figure 20. Based on the observed PHDI time series at the zero threshold the maximum drought durations were observed for larger number of spatial units observed in six time periods (1950’s, 1965’s, 1990’s, 1995’s and in the year of 2000). However, based on the simulated time series the maximum annual drought durations for larger number of spatial units were observed more often, including the drought epochs observed from observed data. The accuracy of simulating maximum annual drought duration increased when the threshold level changed to -2 as it was able to replicate droughts during the 1965’s and the 1990’s as noticed in the observed time series.



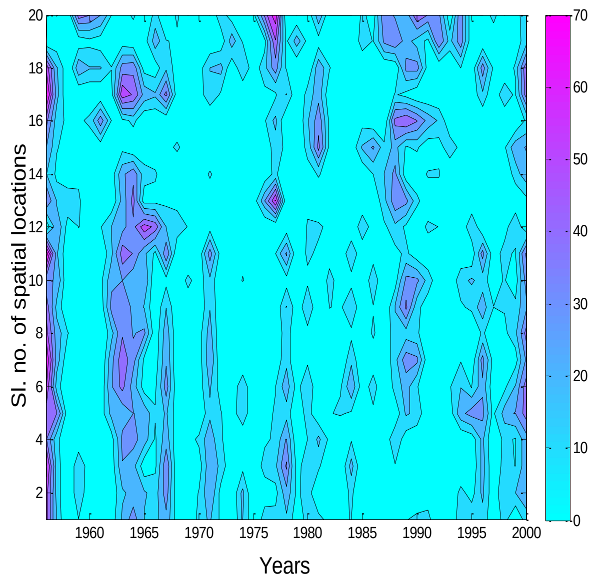
(a) threshold at zero (observed)

(b) threshold at zero (simulated)

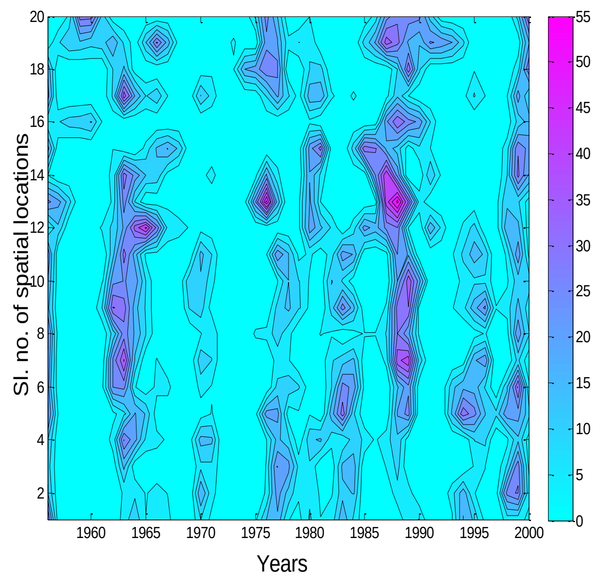
(c) threshold at minus two (observed)

(d) threshold at minus two (simulated)

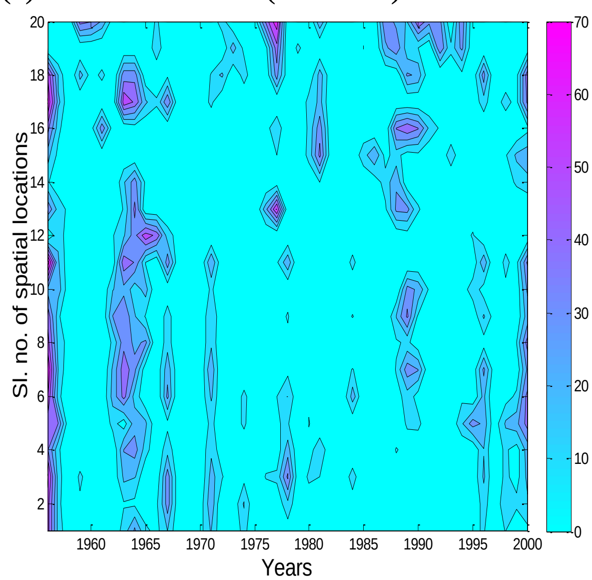
Figure 19. Comparison between observed and simulated annual drought durations on temporal scale for different spatial units.



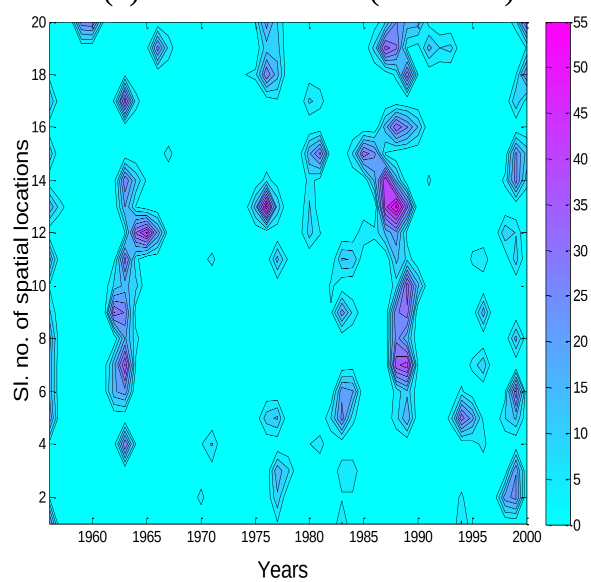
(a) threshold at zero (observed)



(b) threshold at zero (simulated)



(c) threshold at minus two (observed)



(d) threshold at minus two (simulated)

Figure 20. Comparison between observed and simulated annual drought durations on temporal scale for different spatial units.

Predictability of PHDI based on GCM outputs

This section discusses the predictability of PHDI using Global climate models output and observed precipitation and temperature during the period of 1950-2000. To test the predictability the available historical data for GCMs was divided into training set (1950-1985) and testing set (1986-2000). The projected meteorological variables rely on historical observations and thereby provide information for simulating the PHDI time series.

The chosen study area was climate division 1 located in Texas. The observed monthly temperature, precipitation and PHDI time series were collected from the National Climatic Data Center of National Oceanic and Atmospheric Administration. To test the predictability of PHDI time series, the climate projections for different models for A2 scenarios were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. The details can be found in the National Laboratory (LLNL)–Reclamation–Santa Clara University (SCU) multimodal dataset, stored and served out of the LLNL Green Data Oasis (available online at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html). Each WCRP CMIP3 climate projection was bias-corrected and spatially downscaled (Wood et al. 2004 and Maurer 2007) using a two-step procedure: (a) bias correction and, (b) spatial scale downscaling. The statistical properties of annual precipitation time series obtained from multiple GCMs are shown in Table 14 during the period of 1950-2000. The mean annual precipitation during the second half of the century did not vary much among GCMs and the values were lower with respect to the observed time series located in climatic division 1. Both higher and lower standard deviations, kurtosis and skewness were observed in GCMs precipitation output than in observed precipitation.

Table 14. Different GCMs and the statistical properties of their annual precipitation located in Climatic division 1 of Texas for A2 scenarios during the period of 1950-2000.

Sl. No	List of GCMs	Mean (cm)	Standard Deviation (cm)	Kurtosis	Skewness
1	Climatic division 1(Actual data)	47.63	9.07	2.94	-0.22
2	bccr_bcm2_0.1.sresb1	44.96	9.17	2.33	-0.06
3	cccma_cgcm3_1.1.sresb1	45.03	8.61	2.14	0.11
4	cccma_cgcm3_1.2.sresb1	44.86	9.35	2.55	0.13
5	cccma_cgcm3_1.3.sresb1	45.01	10.21	2.94	0.42
6	cccma_cgcm3_1.4.sresb1	45.16	9.86	2.42	0.00
7	cccma_cgcm3_1.5.sresb1	45.21	7.62	2.60	-0.07
8	cnrm_cm3.1.sresb1	45.01	8.97	2.91	-0.58
9	csiro_mk3_0.1.sresb1	45.34	11.48	3.41	0.46
10	gfdl_cm2_0.1.sresb1	44.91	12.78	2.27	0.07
11	gfdl_cm2_1.1.sresb1	45.39	10.36	2.86	-0.54
12	giss_model_e_r.1.sresb1	45.21	6.96	2.11	0.34
13	inmcm3_0.1.sresb1	44.98	9.04	3.44	0.70
14	ipsl_cm4.1.sresb1	44.88	8.59	2.17	-0.11
15	miroc3_2_medres.1.sresb1	45.31	8.36	2.30	0.02
16	miroc3_2_medres.2.sresb1	45.11	9.14	2.33	-0.34
17	miroc3_2_medres.3.sresb1	45.14	8.33	2.96	0.33
18	miub_echo_g.1.sresb1	45.06	7.98	2.93	-0.49
19	miub_echo_g.2.sresb1	44.96	7.57	5.00	1.37
20	miub_echo_g.3.sresb1	45.24	7.47	2.92	0.13
21	mpi_echam5.1.sresb1	45.16	11.05	3.45	0.52
22	mpi_echam5.2.sresb1	44.83	11.33	2.24	0.27
23	mpi_echam5.3.sresb1	44.98	9.83	2.45	-0.13
24	mri_cgcm2_3_2a.1.sresb1	45.19	8.38	2.90	0.15
25	mri_cgcm2_3_2a.2.sresb1	44.91	8.48	3.76	0.84
26	mri_cgcm2_3_2a.3.sresb1	45.09	10.92	2.53	0.11
27	mri_cgcm2_3_2a.4.sresb1	45.11	8.51	3.04	0.62
28	mri_cgcm2_3_2a.5.sresb1	44.88	9.04	2.30	0.31

29	ncar_ccsm3_0.1.sresb1	45.19	8.66	2.05	0.07
30	ncar_ccsm3_0.2.sresb1	45.06	9.37	2.55	0.55
31	ncar_ccsm3_0.3.sresb1	45.39	9.78	2.23	0.16
32	ncar_ccsm3_0.4.sresb1	45.21	10.08	1.99	0.06
33	ncar_ccsm3_0.7.sresb1	45.21	10.34	3.19	0.14
34	ncar_pcm1.2.sresb1	45.01	9.68	2.26	0.29
35	ncar_pcm1.3.sresb1	45.09	9.83	2.47	0.00
36	ukmo_hadcm3.1.sresb1	44.78	9.86	2.76	0.18

Before applying wavelet the Bayesian regression model the correlation coefficient plot was plotted between observed precipitation and temperature monthly time series obtained from (NCDC website, CHECK) and those obtained from GCM's output for the period 1950-2000 as shown in Figure 21. It is worth noting that the CC between observed and different GCM's monthly temperature was found to be consistent and had a value of 0.96, whereas based on the precipitation the CC values fluctuated between 0.35 and 0.5. This preliminary analysis demonstrated that the GCM's were capable of reproducing temperature well, whereas in the case of precipitation it was weak.

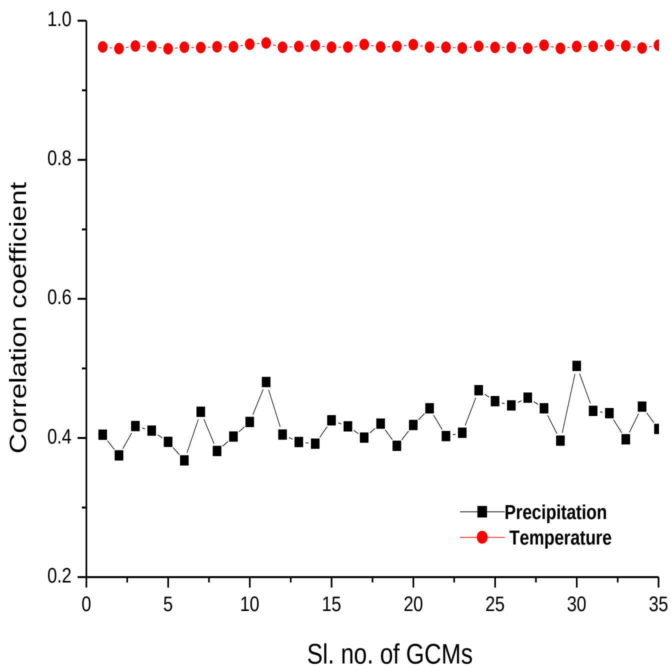


Figure 21. Correlation between observed precipitation and temperature located in climatic division 1 (Texas) with different GCMs (Time period: 1950-2000).

Since precipitation plays an important role in characterizing drought, including PHDI, it will be interesting to look at their predictability using precipitation and temperature obtained from GCMs output. The PHDI time series simulated using the selected GCMs for training (1950-1980) and testing (1981-2000), is shown in Figure 22. It can be observed from the figure that a pattern is noticed during the training period, however during the testing period the pattern is missing. This can be quantified using the CC plot during training and testing periods in simulating PHDI time series (Figure 23). The CC values during the training period vary between

0.4 and 0.7, whereas during the testing set the predictability performance was poor. Therefore it is worth noting that using the GCMs the PHDI time series were not able to simulated properly.

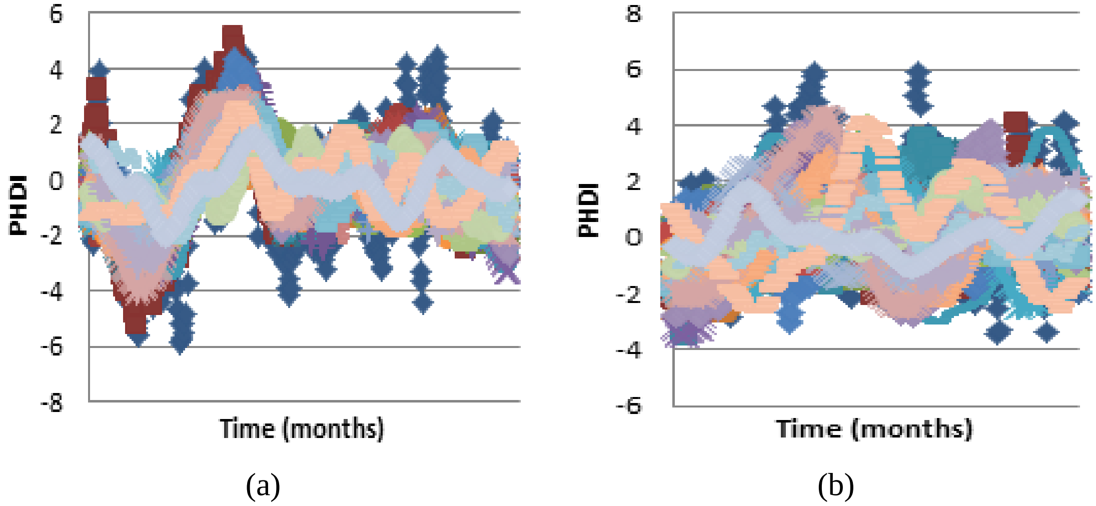


Figure 22. Simulation of PHDI time series during (a) training period (1950-1980), (b) testing period (1981-2000) using selected GCMs.

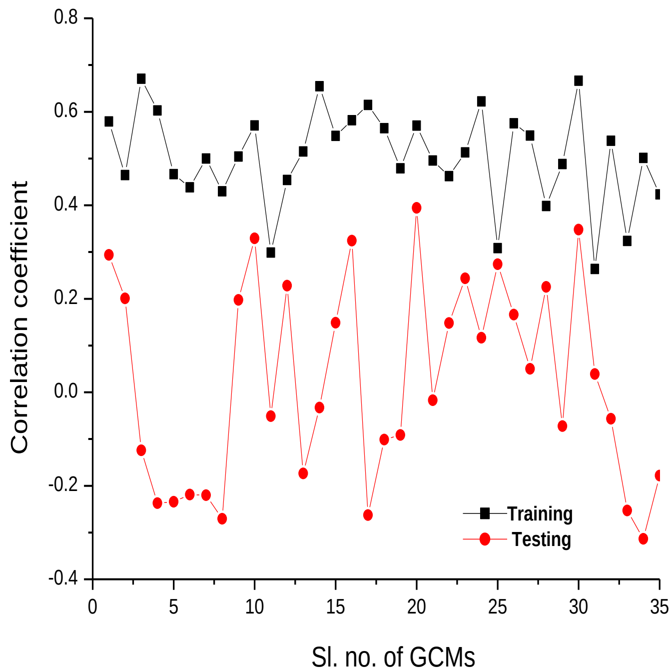


Figure 23. Correlation coefficient between observed and simulated PHDI located in climatic division 1 (Texas) based on wavelet Bayesian regression during training and testing periods for different GCMs.

Conclusion

The following conclusions are drawn from this study:

1. Common drought information is likely to be observed between neighboring climatic divisions, however with the increase in spatial units to a state or regional scale, the quality of information sharing reduces. The number of drought events at regional scale is found to be maximum in northeast, southeast and northwest regions and minimum in the west northcentral region of USA.

2. The wavelet Bayesian regression model performs better than the Bayesian regression model based on different goodness-of-fit results. This advantage results due to the decomposition of PHDI time series into high and low frequency individual time series to capture better information.

3. Using the wavelet Bayesian regression model the performance of precipitation and temperature for simulating PHDI time series at different spatial unit varies, as judged by the goodness-of-fit tests. The performance during the testing period is better at regional units based on the correlation coefficient and a clear pattern is not observed using the root mean square error measure. The bias in the simulation time series is observed to be negative during the training period and positive during the testing period at large number of spatial units. Higher persistence is observed in the simulated PHDI time series in comparison to observed time series.

4. The performance to evaluate annual drought characteristics (severity and duration) decreases in comparison to simulating only PHDI time series. Based on the threshold in selecting drought properties the performance is better at the zero threshold level than at the minus two threshold level. A higher bias is observed in simulating annual drought severity except for the spatial units in northeast, east north central, southeast and northwest region. The maximum positive bias for annual drought severity is observed in the southwest and west regions as the simulated values are lower than the observed values.

5. By changing the threshold levels in identifying the annual drought duration it affects the bias. Using the zero threshold the positive bias is noted in many spatial units, whereas using the minus two threshold negative bias is observed in most of the spatial units.

6. The output from GCMs is able to capture temperature well and it is not observed in the case of precipitation. Therefore, using these GCMs output in simulating PHDI time series does not perform well.

4 (d) Evaporation Research

Evapotraspiration is the primary source by which plants extract water from the soil. In the event of a drought, the role of evapotranspiration becomes even more crucial, because it aggravates the water deficiency. Problems about evapotranspiration (ET) estimation at varying spatial and temporal scales that were addressed included: (1) comparison and contrasting strengths and shortcomings of a series of satellite-based ET estimation models at watershed scales, and evaluating their accuracy based on hydrologic methodologies; (2) improvement of the accuracy of critical inputs for all satellite-based ET estimation models, the instantaneous and daily net radiation, by comprehensively accommodating the effects of terrain on the energy availability for improving the spatial representation and reliability of ET estimates; (3) extension of satellite snapshot latent fluxes to cloudy days and days without good-quality imageries by integration of SEBAL with the GG model; (4) development of a robust entropy-based multi-spectral imagery classification framework to derive land cover maps, providing input for land surface models and ET estimation; (5) quantification of the sensitivity of SEBAL to inputs and investigation of its domain and resolution scale effects. The details of these objectives can be found in the list of publications.

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The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas

Basic Information

Title:	The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas
Project Number:	2009TX335G
Start Date:	8/1/2009
End Date:	7/31/2011
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Focus Category:	Groundwater, Water Quantity, Hydrogeochemistry
Descriptors:	None
Principal Investigators:	Benjamin F Schwartz

Publications

1. Goodsheller, Kelly R., 2011, Differentiation of water use for three dominant species on the Edwards Plateau, MS Thesis, Department of Biology, Texas State University, San Marcos, TX.
2. Dammeyer, Heather Cardella, 2011, Short-term responses of clear-cutting on the water supplies, water status and growth of remaining vegetation: which species have the most to gain? MS Thesis, Department of Biology, Texas State University, San Marcos, TX.
3. Gerst, Jonathan, 2010, Epikarst control on flow and storage at James Cave, VA: An analog for water resource characterization in Shenandoah Valley karst, MS Thesis, Department of Geosciences, Virginia Tech, Blacksburg, VA.
4. Stinson, C. L, B. F. Schwartz, B. W. Tobin, B. R. Gerard, P. Ramirez, G. Timmins, B. Hutchins, and S. Schwinning, 2012, Trinity Aquifer Epikarst Study Using 18O and 2D Stable Isotope Analysis, Cave Without A Name, South-Central Texas (Abstract), Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
5. Tobin, B. W., B. F. Schwartz, B. R. Gerard, P. Ramirez, G. Timmins, B. Hutchins, C. L. Stinson, and S. Schwinning, 2012, Autogenic vs. Allogenic Recharge: Searching for the Source of the Stream in Cave Without A Name, Boerne, TX (Abstract), Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
6. Gerard, B. R., B. F. Schwartz, P. Ramirez, C. L. Stinson, B. W. Tobin, G. Timmins, B. Hutchins, and S. Schwinning, 2012, The Influence of Barometric Pressure Fluctuations on Cave Drip Rates (Abstract), Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
7. Schreiber, M. E., B. F. Schwartz, W. D. Orndorff, J. Gerst, and H. Scott, 2011, Epikarst Control on Quantity and Quality of Recharge to Karst Aquifers: Current Results from Long-Term Monitoring Within James Cave, Virginia (Abstract), Geological Society of America Annual Meeting, Minneapolis, MN, October 8-13, 2011.

8. Gerard, B. R., B. F. Schwartz, and S. Schwinning, 2011, Modeling the Precipitation Threshold Required for Recharge in a Karst Aquifer of Central Texas (Abstract), Geological Society of America Annual Meeting, Minneapolis, MN, October 8 – 13, 2011.
9. Schwartz, B. F., B. R. Gerard, B. W. Tobin, P. Ramirez, B. Hutchins, S. Schwinning, and M. E. Schreiber, 2011, Hydrogeochemical Responses at in-Cave Sites as Indicators of Epikarst Processes: Cave Without A Name, Central Texas, USA (Abstract), Geological Society of America Annual Meeting, Minneapolis, MN, October 8 – 13, 2011.
10. Scott, Heather, M. E. Schreiber, B. F. Schwartz, and W. D. Orndorff, 2011, Spatial and Temporal Patterns of Temperature at James Cave, Virginia (Abstract). Paper No. 6-8. Geological Society of America – Southeastern Section Meeting, Wilmington, NC, March 23-25, 2011.
11. Schwinning, S., K. R. Goodsheller, and B. F. Schwartz, 2010, Fractured Epikarst Bedrock as Water Source for Woody Plants in Savanna (Abstract H11H-0925), AGU Fall Meeting, San Francisco, CA, December 13-17, 2010.
12. Schwartz, B. F., J. Gerst, M. Schreiber, B. W. Tobin, W. Orndorff, D. H. Doctor, and S. Schwinning, 2010, Hydrologic Responses in Epikarst: A Comparative Study Between Virginia and Texas (Abstract), Geological Society of America Annual Meeting, Denver, CO, October 31 – November 3, 2010.
13. Gerst, Jonathan, B. F. Schwartz, M. E. Schreiber, and D. H. Doctor, 2009, Epikarst Role in Controlling the Quality of Karst Aquifer Recharge (Abstract), Geological Society of America Annual Meeting, Portland, OR, October 18-21, 2009.
14. Dammeyer, H. C., K. Goodsheller, S. Schwinning, and B. F. Schwartz, 2009, Changes in tree water status due to clear-cutting in an oak/juniper woodland on the Edwards Plateau (Abstract), Texas Chapter of the Society for Ecological Restoration, New Braunfels, October 6-8, 2009.
15. Goodsheller, K., H. C. Dammeyer, S. Schwinning, and B. F. Schwartz, 2009, Response to extreme drought by three Edwards Plateau tree species: live oak, Ashe juniper and cedar elm (Abstract), Texas Chapter of the Society for Ecological Restoration, New Braunfels, October 6-8, 2009.

Annual report for March 1 2011 – February 28, 2012

Title: The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas

Project Number: 2009TX335G

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Focus Category: Groundwater, Water Quantity, Hydrogeochemistry

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Principle Investigator: Benjamin F. Schwartz, Texas State University

Co-PIs: Madeline E. Schreiber, Virginia Polytechnic Institute and State University; and Daniel H. Doctor, U.S. Geological Survey.

Abstract:

The epikarst, often called the "skin" of karst aquifers, is a critical zone that significantly influences hydrology, water quality, and ecosystems in karst aquifer systems. The epikarst regulates both the quantity and quality of autogenic recharge to karst aquifers and, as a result, may be the most important component of the system. However, due to its extreme heterogeneity, the epikarst is notoriously difficult to characterize. Our primary research objective is to use interdisciplinary methods in a 'holistic' approach to studying the epikarst at different scales in diverse geologic and climatic settings. With this approach we expect to answer many questions about the mechanisms and processes controlling movement and quality of water between the surface and karstic aquifers that are otherwise difficult to answer.

To accomplish this, we have already installed instrumentation at four research sites in the shallow Virginia James Cave (beginning in late 2007) and at five research sites in four different shallow Texas caves (beginning in late 2008) and have collected preliminary hydrologic, geochemical and biologic data. Each station is instrumented to allow continuous measurements and periodic sampling of hydrologic (precipitation and drip rates), geochemical (pH, temperature, redox

potential, specific conductance, dissolved oxygen, major ions) and biological (copepod and other invertebrates) parameters. In-cave drip sites have been chosen where cave ceilings are within 15 m of the surface to ensure proximity to the hydrogeologically complex epikarst zone. This is within the generally accepted vertical limit of the epikarst (15m) in most regions. In Virginia, James Cave is located in a low-relief, autogenically recharged karst region in Pulaski County; representative of much of the Shenandoah Valley and other karst regions in Virginia. In Texas, the four caves are located on the eastern edge of the Edwards Plateau between Austin and San Antonio in autogenic portions of the sensitive recharge zone for the Edwards Aquifer. These preliminary data prove that we are able to detect changes in epikarst parameters that are related to local climatic and geologic conditions. However, we are currently limited to investigating small-scale drips sites and one in-cave stream. To determine how epikarst water parameters are related to the quantity and quality of groundwater in the entire aquifer system, we need to expand the study to include nearby groundwater, springs, and other cave streams.

For this study, we propose to extend data collection by 2 additional years for drip rate, continuous geochemical parameters, water chemistry, and invertebrate biology in the James Cave system, and to expand the scope and scale of the project to monitor chemistry and discharge at the cave spring and measure water levels in local wells installed in the phreatic zone. We will also expand on the study in both states by analyzing water from drips, soil water, precipitation, and ground water sources for: major ions, inorganic and organic carbon, water stable isotopes ($^{18}O/^{16}O$, $^{2}H/^{1}H$), and $^{13}C/^{12}C$ of inorganic and organic carbon species.

Our results will also be applicable to paleoclimate studies using speleothems by determining how epikarst processes affect the composition of drip waters forming speleothems. From a biological perspective, very little work has been done investigating the epikarstic fauna in North America and our results will make a significant contribution to knowledge about epikarstic fauna in the region.

To our knowledge, this study will mark the first time that biology has been used in conjunction with continuous hydrologic and geochemical monitoring, which we believe will allow epikarstic fauna to be used as a proxy for hydrogeochemical conditions in and structure of the epikarst. We will use our results to support the design and implementation of studies at larger scales, with the ultimate goal of characterizing the small scale processes in the epikarst that influence the quantity and quality of water in a larger karst aquifer system.

Problems and Research Objectives:

The primary objective of this research was to answer the following questions: 1) What factors determine thresholds of water excess (precipitation-evapotranspiration) that must be crossed in order to generate recharge to karst aquifers?; 2) How do water quality and biological community diversity vary under different conditions of recharge?; and 3) How do recharge responses through the epikarst scale up to aquifer response and ground water flow on a catchment scale?

Materials and Methodology:

Texas:

In Texas, field research supported by the USGS funding has recently been completed (April, 2012) and research is now entering a phase of data analysis and publication. Data collection continued through one of the most severe one-year droughts the region has ever experienced during most of 2011, and into period of several months with average rainfall during late 2011 and early 2012. This has allowed us to collect data from two drought periods and two wet periods, and to begin understanding how the system responds under these very different hydrologic conditions.

At each of our three sites in TX, weather data and precipitation samples were collected on the surface. In the caves at each of the sites, periodic water samples for geochemical and stable isotope analyses, and continuous hydrogeochemical parameters were measured at a variety of sites including drip sites with variable precipitation response times, an in-cave stream, and a nearby well.

We applied for and received a one-year no-cost extension for the project. Because the transfer of funds was significantly delayed beyond the original start-date, this allows our project completion date to be 7-31-2012 rather than 7-31-2011, which means that we will have enough data for meaningful analyses before completion of a final report.

A manuscript resulting from work by one of the graduate students that graduated in Fall 2010 has been submitted for publication in the Journal Oecologia, has been reviewed, and is under revision. Two other graduate students that started on this project in Fall 2010 and Fall 2011, are on track to defend their theses ~2.5 years after beginning studies, and both will also be publishing their results in peer-reviewed journals.

Virginia:

At the Virginia site, James Cave, progress also continues to be very good, with a fifth year of data collected during 2011-2012. The instrumentation and sampling at James Cave has been streamlined to allow for more efficient use of limited time by volunteer staff. Rather than collecting a full suite of continuous geochemical parameters at each site, we decided to focus on parameters for which sensors are stable and more reliable without frequent calibration. All sites are now instrumented for continuous drip/flow rate, temperature, and specific conductivity

Stable isotope samples are still being collected monthly and will be used to continue our investigation of residence times, storage, and flow velocity in the epikarst.

To summarize, the no-cost extension to this funding has allowed us to continue monitoring and sampling for a fifth year at the James Cave site at a stream, three drip sites, and a surface site. Additionally, lysimeters that were installed in soils above the in-cave sites and water samples are routinely being sampled. One graduate student successfully completed his thesis, another has begun her thesis, and we are in the process of preparing two manuscripts from his work, which will be submitted for publication in peer-reviewed journals.

Work Summary:

Over the past 12 months, numerous visits have been made to maintain equipment installed both on the surface and underground. In Texas, since the end of the 2009 drought, frequent visits have been made to maintain equipment, download data, and collect samples. One intensive sampling period occurred at one of the sites, in which high-frequency samples were collected before, during, and after a major storm event. This has allowed us to use mixing models to calculate the percentage of precipitation event water that reached each of the monitoring sites, and to model how each of the sites responds differently to this type of event.

In Virginia, trips to the surface site and into the cave are now limited to once each month due to logistics. One graduate student defended his thesis on the VA work, and another recruited in 2011. Two graduate students defended their theses on work at the TX sites, and two additional graduate students were recruited to work on the TX sites. Several other students (both graduate and undergraduate) have helped with work on the projects.

Principal Findings:

What follows is a summary of our preliminary findings over the past 2 years.

Texas

Because we have recently experienced a change from drought conditions to slightly wetter, and now back into drought conditions, we are collecting important information that is finally allowing us to better understand the dynamics of infiltration, flow, and recharge into and through the epikarst.

In Headquarters Cave, McCarty Cave, and Cave Without A Name (CWAN), drip rates slowed or nearly stopped during 2009, recovered after the rains in the fall season of 2009, and have steadily declined since rainfall decreased in September 2010 through October 2011. After a brief period of average precipitation from October 2010 to March 2011, we are again in a serious hydrologic drought in TX, and geochemical and drip data are revealing how the epikarst responds to the second extended period of depletion by drainage and ET on the surface.

Preliminary analysis of the time-series drip rate data has resulted in several interesting findings. These can be summarized as follows:

1) Drip rates appear to be controlled by variable amounts of storage in bedrock matrix, as well as some rapid flow during wet periods, which is allowing us to investigate what we believe to be a representative range of the flow systems in the epikarst. For example, some sites respond only briefly to large rain events and completely dry up, while others drip continuously and appear to have very slight responses to large rain events, but with a ~4-month lag time. A graduate student (Brett Gerard) has nearly completed a model which can be used to predict if and how much a drip site will respond to a rain event. This is important, because a drip response indicates that recharge is occurring, which implies that this model may be useful for modeling the amount and timing of recharge in the region.

2) At all sites (VA and TX), close investigation of 'noise' in drip rates has revealed that the drip rate responds inversely to changes in barometric pressure. Work to understand and model these responses is in intermediate stages and we anticipate that the results can be used to estimate epikarst hydraulic properties such as storage and hydraulic conductivity.

3) Long term drip records at some of the sites in TX show that there is a perched aquifer system which drains through a fracture leading to the monitoring site. The perched aquifer has different storage and hydraulic conductivity properties. Once depleted, the drip rate drops sharply to a new baseflow level. A certain amount of precipitation is then required to reach a recharge/infiltration threshold where drainage from the perched aquifer is re-activated. This site has also provided data which indicates that the effects of a drought on epikarst storage take more than a short re-wetting period to fully recover from.

At the TX sites, storage in the matrix supports baseflows at drip sites for long periods of time and (for some sites) attenuates signals from precipitation events. In contrast, bedrock matrix storage appears to be much less important at the Virginia site and precipitation signals at drip sites are dominated by seasonality of ET.

<u>Virginia</u>

With this funding, we have extended our collection of long term records of hydrologic and geochemical data in James Cave. We continue to examine the role of epikarst in controlling the quantity and geochemical evolution of recharge water as it passes through the epikarst.

Data collected from September 2007 to present are being used to identify trends in the temporal and spatial distribution of recharge to underlying aquifer. Results show that water-rock interactions and anthropogenic inputs (e.g., manure, fertilizer, and road salt) have significant impacts on the water quality of recharge (e.g, levels of Nitrate well above the drinking water standard at one drip site). However, samples from the main stream in the cave rarely show elevated Nitrate levels, indicating that they may be attenuated by microbial processes, or that our drip sites do not represent the larger baseflow contributions to the stream (and high levels are being diluted), or that we have simply not sampled the main stream at a time when large pulses of Nitrate are being flushed through the system.

Geochemical signatures of different water types (precipitation, soil water, epikarst drips, cave stream) are still being used to estimate the degree of evolution and residence time of recharge and infiltration through the epikarst. As is typical with karst systems, heterogeneity exists in the epikarst; however all sites share similar hydrologic and geochemical responses to recharge events. Drip rate patterns conclusively indicate that recharge through the epikarst occurs during late winter/spring, and is almost negligible during the summer due to high evapotranspiration. However, recharge may continue from late spring and into the early summer during exceptionally wet years. Analysis of water stable isotopes is being used to estimate retention time and storage/dilution of water in epikarst.

By assessing the timing and quality of recharge, both during base flow conditions and in response to multiple recharge events of varying magnitudes, we are able to use the results from James Cave as an analog for watersheds in the greater Shenandoah Valley region. This was one of our primary objectives of the research, and it allows managers to better understand and characterize the role of epikarst in controlling recharge and water quality in similar karst aquifers.

Significance:

Between the funding provided through the NIWR and two other earlier grants, we now have enough data from several different sites in two different climatic regions that we can begin to understand the how the shallow epikarst functions over a variety of spatial scales and over multiple years. This is important, especially in TX because of multi-year cycles of drought and rain, as opposed to the more seasonal cycles experienced in the Virginia site.

Student involvement:

Student involvement has been a critical component of research at both sites and has included many students at all levels of involvement ranging from occasionally assisting a graduate student on a volunteer basis, to being paid on an hourly basis, to being funded to perform graduate research. All students and P.I.s have benefited tremendously from these opportunities.

Six graduate students and four undergraduate students are or have been intimately involved with various aspects of the TX portion of this research, including thesis work related to the project for three of the graduate students. An additional graduate student will begin work on the project in Fall 2011.

In Virginia, one graduate student completed his thesis in 2010, a second graduate student has been recruited to work on the project, and three other graduate and two undergraduate students have supported the continuing sampling and data collection at the site.

Publications:

To date, two theses and a number of abstracts have been published during this project, including the 12 listed below. Other work has been presented in Departmental Graduate Research Symposia, local meetings, and during field trips for an Ecolicical Society of America field trip (TX, 2011) and a trip for Hays County Master Naturalists (TX, 2012). Additional publications will result from this work as data analysis continues and will be in the form of journal articles, theses, and abstracts.

Theses:

1) Goodsheller, Kelly R., 2011, Differentiation of water use for three dominant species on the Edwards Plateau. MS Thesis, Department of Biology, Texas State University, San Marcos, TX.
2) Dammeyer, Heather Cardella, 2011, Short-term responses of clear-cutting on the water supplies, water status and growth of remaining vegetation: which species have the most to gain? MS Thesis, Department of Biology, Texas State University, San Marcos, TX.
3) Gerst, Jonathan, 2010, Epikarst control on flow and storage at James Cave, VA: An analog for water resource characterization in Shenandoah Valley karst. MS Thesis, Department of Geosciences, Virginia Tech, Blacksburg, VA.

Abstracts:

1) Stinson, C. L, **Schwartz, B. F.,** Tobin, B. W., Gerard, B. R., Ramirez, P., Timmins, G., Hutchins, B., and Schwinning, S. Trinity Aquifer Epikarst Study Using $\delta^{18}O$ and $\delta^{2}D$ Stable Isotope Analysis, Cave Without A Name, South-Central Texas. Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
2) Tobin, B. W., **Schwartz, B. F.,** Gerard, B. R., Ramirez, P., Timmins, G., Hutchins, B., Stinson, C. L., and Schwinning, S. Autogenic vs. Allogenic Recharge: Searching for the Source of the Stream in Cave Without A Name, Boerne, TX. Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
3) Gerard, B. R., **Schwartz, B. F.,** Ramirez, P., Stinson, C. L., Tobin, B. W., Timmins, G., Hutchins, B., and Schwinning, S. The Influence of Barometric Pressure Fluctuations on Cave Drip Rates. Geological Society of America, South-Central Section Annual Meeting, Alpine, TX, March 8-9, 2012.
4) Schreiber, M. E., **Schwartz, B. F.,** Orndorff, W. D., Gerst, J., and Scott, H.. Epikarst Control on Quantity and Quality of Recharge to Karst Aquifers: Current Results from Long-Term Monitoring Within James Cave, Virginia. Geological Society of America Annual Meeting, Minneapolis, MN, October 8 – 13, 2011.
5) Gerard, B. R., **Schwartz, B. F.,** and Schwinning, S., Modeling the Precipitation Threshold Required for Recharge in a Karst Aquifer of Central Texas. Geological Society of America Annual Meeting, Minneapolis, MN, October 8 – 13, 2011.

6) **Schwartz, B. F.,** Gerard, B. R., Tobin, B. W., Ramirez, P., Hutchins, B., Schwinning, S. and Schreiber, M. E., Hydrogeochemical Responses at in-Cave Sites as Indicators of Epikarst Processes: Cave Without A Name, Central Texas, USA. Geological Society of America Annual Meeting, Minneapolis, MN, October 8 – 13, 2011.
7) Scott, Heather, Schreiber, M. E., **Schwartz, B. F.** Orndorff, W. D. Spatial and Temporal Patterns of Temperature at James Cave, Virginia. Paper No. 6-8. Geological Society of America – Southeastern Section Meeting, Wilmington, NC, March 23-25, 2011.
8) Schwinning, S., Goodsheller, K. R., **Schwartz, B. F.** Fractured Epikarst Bedrock as Water Source for Woody Plants in Savanna. Abstract H11H-0925. AGU Fall Meeting, San Francisco, CA, December 13-17, 2010.
9) **Schwartz, B. F.,** Gerst, J., Schreiber, M., Tobin, B. W., Orndorff, W., Doctor, D. H., Schwinning, S. Hydrologic Responses in Epikarst: A Comparative Study Between Virginia and Texas. Geological Society of America Annual Meeting, Denver, CO, October 31 – November 3, 2010.
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11) Dammeyer, H. C., Goodsheller, K., Schwinning, S., **Schwartz, B. F.** Changes in tree water status due to clear-cutting in an oak/juniper woodland on the Edwards Plateau. Texas Chapter of the Society for Ecological Restoration, New Braunfels, October 6-8, 2009.
12) Goodsheller, K., Dammeyer, H.C., Schwinning, S., **Schwartz, B. F.** Response to extreme drought by three Edwards Plateau tree species: live oak, Ashe juniper and cedar elm. Texas Chapter of the Society for Ecological Restoration, New Braunfels, October 6-8, 2009.

Institutional Mechanisms for Accessing Irrigation District Water

Basic Information

Title:	Institutional Mechanisms for Accessing Irrigation District Water
Project Number:	2010TX375G
Start Date:	9/1/2010
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	17
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, Economics, Water Supply
Descriptors:	
Principal Investigators:	Ron Griffin

Publications

1. Griffin, Ronald C., 2012, Engaging Irrigation Organizations in Water Reallocation, Natural Resources Journal, forthcoming 2012.
2. Griffin, Ronald C., 2012, The Origins and Ideals of Water Resource Economics in the U.S., Annual Review of Resource Economics 4, forthcoming 2012.
3. Ghimire, Narishwar, 2012, Engaging Irrigation Organizations in Water Reallocation, Natural Resources Journal, in-progress.
4. Griffin, Ron, and Mary Kelly, 2012, The Future of Irrigation Organizations in the Colorado River Basin, The Water Report 95 (January 15, 2012, www.thewaterreport.com): 18-22.

Progress Report

Title: Institutional Mechanisms for Accessing Irrigation District Water

Award Number: G10AP00138

Primary PI: Ronald C. Griffin

Other PIs: none

Abstract (from the proposal)

Given (1) large water holdings by irrigation districts, (2) rising scarcity in areas where districts operate, (3) the high costs and coming impracticality of water supply expansions, and (4) the unrealized potential for irrigation districts to contribute solutions to the scarcity problem, the research proposes to study policy alternatives. Instances where districts currently participate in reallocations are typically failing to provide least-cost water or to optimize irrigator welfare. Options for better enlisting aid from irrigation districts will be inventoried and characterized. Economic analysis will be performed with the guiding objective of identifying solutions that can succeed in being efficient as well as attractive to district clients. Methods of microeconomic modeling, econometric analysis, and institutional economics will be applied.

Problem and Research Objectives (from the proposal)

Irrigation districts are very prominent destinations for a large portion of the nation's water. For various reasons, their proportion of water use is unmatched by participation in growth-induced water reallocation to municipal and industrial sectors. As observed by Thompson "most water districts have been hostile to external transfers – particularly to long-term ag-urban trades" (1993, p. 728). This continues to be true and is increasingly problematic in light of rising scarcity. Avenues for improving these situations are likely to have different properties, and some may have comparative advantages over others. This study proposes to investigate this situation and examine policy options for their prospective efficiency characteristics and appeal to district clientele.

Continued population pressure, particularly in the West, South, and Southeastern United States, is exacerbating water scarcity. Much has been written about this matter, and much of this literature underscores the impracticality of developing new water supplies sufficient to mitigate the growing problem. Available supply development options are expensive – this fact is corollary to the existence of scarcity – thereby inferring that supplyside options are increasingly unattractive (and ultimately infeasible) relative to demand management policies. This message has been slow to penetrate policy, yet it is the task of research to be proactive and lay foundations for the future's crucial solutions.

In addition to the large expense of contemporary supply development options, it should be recognized that some of the supplyside options are energy- and/or environmentally intensive, severely limiting their attractiveness even in the short term. Overall, silver bullets are not in sight. Thus, for many regions of the nation, it will be increasingly important to uncover (or rediscover) ways of living within the currently developed water supply and existing levels of infrastructure.

A rising new force is that climate change is accentuating the scarcity problem for those U.S. regions already impacted by water scarcity. Snowpack is becoming a less generous and less reliable reservoir. The Southwest in general, and the Colorado River basin in particular, may be especially threatened by this problem. More widely, heightened volatility in precipitation is causing reservoir operators to pay greater attention to flood protection, to the detriment of water supply objectives. Complementing climate change, the so-called "energy-water nexus" is raising realizations that interconnected use and production of these two resources may link their values in underappreciated ways. Therefore, it becomes risky to address water scarcity issues by relying on potentially energy-intensive measures (e.g. interbasin conveyances and desalinization).

For these reasons and others, the nation must look inward. Old expectations, established behaviors, and prior norms merit reexamination. To accommodate unequally growing water demands, it is actually efficient for some sectors and users to end up with less water so that others can have more (zero sum). Water reallocation and new sharing prescriptions are likely to evolve into pivotal tools for this reason. Ideally, the needed changes can be designed so that efficient change is not obstructed by factions who perceive themselves to be losers in reallocation. So compensation mechanisms are arguably crucial strategies, to appease those agents who sacrifice water and to create enthusiasm for developing and exploiting new conservation options.

Along these lines, water marketing is economics' poster child example of a win-win institution for fostering efficient reallocation. This policy option has yet to produce all the promises it seems capable of. Although agriculture-to-urban and agriculture-to-environment transfers have begun to make strong social contributions in addressing scarcity, hurdles and unimagined boundaries have arisen. One of these problems has involved the weak voluntary participation of irrigation districts in water reallocation. This is not to assert that IDs have never assisted in reallocation, just that they have approached it reluctantly and with underperforming results in the sense of identifying least-cost solutions or maximizing aid to their irrigator clients. Also, there is casual evidence that privately held irrigation rights (by farmers not connected to IDs) have been readily transferred to cities, to the extent that this pool has been depleted in some areas.

Though the available options have never been inventoried (to the PI's knowledge), every state can employ an array of policies to allow or motivate IDs to interact with other sectors. It is not possible to classify all of these approaches as water marketing tactics, yet some of them employ marketing or adapt it in some fashion.

To illustrate some of the conceivable avenues for bettering ID cooperation, here is a short list of actual and theoretical opportunities:

1. IDs can commence direct service to nonirrigating clients. Here, the ID adopts the role of a general water utility and becomes a multisectoral water supplier with a declining focus upon irrigation over time as nonagricultural sectors grow.

   Notes: This option is not ordinarily invoked unless existing infrastructure can be conjunctively used to serve nonirrigators as well as irrigators, inferring that new user groups must be located proximate to the district's facilities. Inevitably, this strategy expands the decision-making community involved in the ID's policy development and, for good or bad, politicizes (internal to the district) the future reallocation of water to growing nonirrigation sectors. For example, the ID must set an broader array of rates, which influence use, usually establishing different irrigation and urban rates. Moreover, the transition to direct service distances irrigators from the possibility of gaining title to water, thereby altering their future willingness to voluntarily conserve. The internal transaction costs of this nonmarket approach may be high, as the ID's clients may have to continually revisit and debate district policy due to continued issues with limited water and financing.

2. IDs can directly contract with external buyers and use the proceeds to fund water-saving infrastructural improvements of district-owned facilities. Water savings are received by the buyers. On-farm water use is not directly modified.

   Notes: This option has seen limited practice. Issues include continued maintenance of the improvements, the fact that these expenditures are not least-cost options until low-valued irrigation has been eliminated, and the influx of money may result in lower water rates for irrigators thereby spurring interest in additional, not reduced, irrigation. These problems constrain net gains to both irrigators and buyers.

3. IDs can directly contract with buyers and use the new funds to elicit on-farm modifications. Water savings are received by the buyers. On-farm changes might be focused on water-conserving infrastructural or land improvements, cropping changes, or fallowing.

   Notes: This option has seen very limited practice. When an in-district auctioning process is used to enlist irrigators, there can be improved confidence that least-valued activities are being eliminated. From a districtwide perspective acknowledging the possibility of idling particular canal segments (and conserving conveyance losses as well as on-farm use) and generally constricting the irrigated service region over time, auction mechanisms may not be fully least cost and therefore may not be generating the greatest rewards for ID clients.

4. When an ID's water rights are explicitly partitioned across individual irrigator clients and these irrigators are allowed to contract with outside parties, reallocation amenable to irrigators and buyers can be achieved.

   Notes: This option has been practiced within "mutual" irrigation organizations such as the Northern Colorado Water Conservancy District. There are likely to be third party effects upon the ID that stem from return flow consequences or conveyance loss considerations. Policy adjustments for these issues may be warranted.

5. IDs can revise their rates to include a volumetric water price that incorporates a regionally appropriate scarcity value for water. The induced reductions in water use can then be marketed to external buyers. Market proceeds can be distributed among irrigators as dividends.

   Notes: This option has not been practiced. Observe that the embedded scarcity value and water market value will ordinarily have to be synchronized. Also, dividends to irrigators must not be based on water use reductions: to do so undermines the conservation incentive attached to rates.

6. Paralleling the case of electricity deregulation and the decoupling of electricity production from electricity delivery, IDs could be legally separated into two entities.

The traditional entity would own/operate all conveyance infrastructure and pursue its originally designated duties. The new entity would hold all water rights, pursue profits, and irrigators would be its major shareholders.

Notes: This option has not been practiced. Results of this approach are likely to be similar to #5. It may be desirable to attend to ordinary conveyance losses by making the traditional entity a shareholder in the new entity, with shares proportioned according to conveyance losses.

The list is intended to be suggestive; it is not exhaustive. Listed alternatives include overlapping measures, and some of them can be blended or employed conjunctively. Other possibilities such as regulatory options and purchases/condemnations of IDs by cities are not included because project emphasis is upon voluntary mechanisms. Some of the candidates are not currently allowed because either (a) the ID nor its clients hold transferrable water rights (as they are still held by the original project developer, such as the U.S. Bureau of Reclamation) or (b) state law has yet to sanction the transferability of water rights. In these two cases, obvious legal changes are required before certain measures can be conducted.

Therefore, a full, original study of these opportunities is warranted by

- *the importance of better aligning every region's water use with its water budget,*
- *the significance of gaining fuller ID participation in addressing the national water scarcity problem, and*
- *the diversity of the multiple alternatives available for interfacing ID's with external sectors.*

Objectives

1. Develop quantitative information on the extent of irrigation district entitlements to surface water in Western and Southern states.
2. Inventory and characterize options (including novel and nonincremental approaches) for engaging U.S. irrigation districts as parties to water reallocation to higher value uses in both irrigation and nonirrigation sectors.
3. Develop microeconomic models featuring irrigation districts of variable parameters and farm plus canal heterogeneity interfacing with external water demand sectors.
4. Assemble data for panels of irrigation districts and pursue empirical analyses as suggested by microeconomic formulations and as enabled by available data.

Progress and Accomplishments

Literature reviews and investigations of data availability are complete. The inventory of policy options for improving the participation of irrigation organizations (IOs) in water reallocation is complete. The PI's participation in Western Governors Association panel on the future of water marketing allowed this work to be shared with other western experts and policy makers in the area. An academic paper by the PI was produced from this work and is forthcoming in the *Natural Resources Journal*. A trade-oriented paper drawn from this work was coauthored by the PI and was published in *The Water Report* during January 2012. The historical research performed by the PI as a consequence of this project contributed to the production of another article which has recently been accepted for publication in the *Annual Review of Resource Economics*.

The doctoral research assistant for this project (Mr. Ghimire) developed and presented a paper entitled “Irrigation Districts and Water Reallocation in the Western U.S.” at the November 2011 meeting of the American Water Resources Association held in Albuquerque. Chapter II of Mr. Ghimire's in-progress dissertation is largely built based on inputs from this paper.

The remainder of this section of the progress report was prepared by Mr. Ghimire.

Data and methods to be used for the dissertation are nearly finalized. The dissertation has three objectives:

1. Analyze economic and political behavior of IDs in relation to agriculture-to-urban water trading in the western U.S.
2. Examine behavioral differences in external water transfers among IDs and non-IDs in the Rio Grande Valley of Texas.
3. Investigate the heterogeneity of IDs and its implication for external water transfers in the Rio Grande Valley of Texas.

Chapter II deals about institutional structure of irrigation districts and water reallocation in the American West. The purpose of the chapter is to uncover how the economic and political structure of irrigation districts designed to further the irrigation development in the past has undermined reallocation of water to higher valued sectors in the West in the changing economic reality. The chapter is purely an institutional analysis based on the past literatures. In Chapter III an attempt has been made to answer the question of whether there is any behavioral differences in water rights transfer responses among irrigation districts and non-districts (private corporations) using empirical techniques. The Rio Grande Valley in Texas has been selected for the study site for its unique blend of districts and non-districts where water transfer activities have been undergoing for decades, making a panel-type study possible. In Chapter IV a micro level study about the heterogeneity of irrigation districts in terms of initial water right holdings and its implication for water transfers has been proposed. This is largely based on the cross-sectional and time series water transfers data extracted from the amendments to water rights adjudication in the Rio Grande Valley.

Data for study have been obtained from the Texas Commission for Environmental Quality (TCEQ), Austin. The central file room of the TCEQ at Austin was visited number of times to obtain information about water rights transfer data. The data were extracted from the amendments to water rights adjudication as discussed earlier. The amendments include change in purpose of water rights, point, place, or point of diversion, or any alterations in water rights conditions. For the purpose transfer has been defined as the change in purpose of water use from agriculture to municipal use. During May 2011 the officials at water rights permitting section of the TCEQ were consulted to learn about water rights database and transfer procedure of water in the state of Texas. In June 2011 the central file room was visited to plan a procedure of obtaining information about water rights and amendments for the selected water right accounts in Texas. Most of the information about water rights and amendments before 2002 was found to be stored in microfilms and microfiches. It took almost two weeks (July 5-15, 2011) to obtain information about water rights amendments of about 100 water right accounts that were listed as industrial and municipal water users. Extraction of transfer data from the amendments took several weeks. A total of 480 amendments were reviewed of which about 368 are about water transfers.

A trip was also organized to visit a number of irrigation districts in the Lower Rio Grande Valley in September 11-16, 2011. The irrigation districts visited were the United Irrigation District, Harlingen Irrigation District Cameron County#1, Hidalgo County ID #6, Hidalgo and Cameron County ID #9, Cameron County Water Improvement District#16, and Cameron County ID#2. Some of the irrigation infrastructures such as canals and water pumping plants were observed with the managers of Harlingen IDCC#1 and United ID. The main purpose for the visit was to understand the current conditions, operating procedures, laws/bylaws of irrigation districts, water transfer activities, obstacles to transfers, and to validate or cross-check some of the water transfer data obtained from the TCFQ, Austin. The Watermasters' office at Harlingen was also visited to get information about the number of irrigation districts currently functional in the Valley, water right accounts, and their historical water right holdings in the valley.

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Publications

Articles in Refereed Scientific Journals

Ronald C. Griffin. "Engaging Irrigation Organizations in Water Reallocation." *Natural Resources Journal*. Forthcoming 2012.

Ronald C. Griffin. "The Origins and Ideals of Water Resource Economics in the U.S." *Annual Review of Resource Economics* 4. Forthcoming 2012.

Dissertations

Narishwar Ghimire. "Engaging Irrigation Organizations in Water Reallocation." *Natural Resources Journal*. In-progress.

Other Publications

Ron Griffin and Mary Kelly. "The Future of Irrigation Organizations in the Colorado River Basin." *The Water Report* 95 (January 15, 2012, www.thewaterreport.com): 18-22.

Assessing Low Ear Placement Corn Hybrids as a Way of Increasing Water Use Efficiency

Basic Information

Title:	Assessing Low Ear Placement Corn Hybrids as a Way of Increasing Water Use Efficiency
Project Number:	2011TX390B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	13th
Research Category:	Ecological Processes
Focus Category:	Irrigation, Agriculture, Water Use
Descriptors:	None
Principal Investigators:	Jacob Becker, Brent Bean

Publications

There are no publications.

Drought Tolerant Corn Hybrids as a way of Increasing Water Use Efficiency

PROGRESS REPORT

Project Number: 2011TX390B

Primary Investigator: Jacob Becker

Other Investigators: Brent Bean, Brock Blaser

Prepared for the Texas Water Resources Institute with funding provided by United States Geological Survey

PROGRESS REPORT

Title: Drought Tolerant Corn Hybrids as a way of Increasing Water Use Efficiency

Project Number: 2011TX390B

Primary PI: Jacob Becker

Other PIs: Brent Bean, Brock Blaser

Abstract

Texas corn producers are able to obtain corn yields that rival that of any region in the world. Without irrigation from the declining Ogallala aquifer, these yields would not be possible. Over the past 50 years, tremendous advances have been made in improving irrigation efficiency. However, many producers are turning to limited irrigation, because of the dwindling water supply and implemented water pumping restrictions from regional water authorities. Irrigation application, planting population and hybrid selection can all play important roles in determining water use efficiency (WUE). Two separate studies were planted in 2011 at the North Plains Research Field (NPRF) in Etter, TX, comparing the first generation drought tolerant hybrid corn technologies from Pioneer and Syngenta. Irrigation rates were set at 100%, 75%, 50% and 40% of evapotranspiration (ET). A low, medium and high population was selected for each company. The highest water use efficiency (WUE) was observed at 75% ET with 40,000 seeds acre^{-1} at 8.64 bushels acre^{-1} inch^{-1} of total water. Population effects were related to hybrids and irrigation level. In general, the commercially available drought tolerant hybrids showed an increase in yield over the check hybrids at lower water levels. Pollination also improved with a drought tolerant hybrid in the 50% and 40% irrigation levels when compared with a check. 2011 was an exceptional year of drought and heat in the Southern High Plains. This should be taken into consideration when interpreting these results.

Problem and Research Objectives

The Southern High Plains sits at the Southern edge of the largest aquifer system in the world. The Ogallala aquifer is a confined aquifer that can vary in water depth from 0 to 1200 feet. With above ground municipal water supplies falling to all-time lows, cities are looking towards the aquifer to meet their needs. With agriculture pumping approximately 70% of the water out of the aquifer, increased pressure will be continually placed on producers to limit their water use. Water restrictions placed on producers or a dwindling water supply would be detrimental to a major cropping system in the Southern High Plains. Corn is a major irrigated crop in the Texas Panhandle. With producers' water supply becoming more limiting year after year, WUE must be increased to conserve water in the Ogallala while maintaining a sustainable cropping system that includes corn.

These studies were meant to examine corn hybrids at varying irrigation levels, seeding rates and hybrids to determine the water use efficiency. This data will ultimately be used by producers in the Southern High Plains to make production decisions about full and limited irrigated corn by applying production functions created from this research.

Materials/Methodology

Research was primarily conducted at the North Plains Research Field (NPRF) in Etter, TX (approximately 60 miles north of Amarillo, TX). Four irrigation levels were set at 100%, 75%, 50% and 40% of evapotranspiration (ET). 29.7, 23.0, 16.3 and 14.1 inches of water were applied in the four irrigation levels, respectively. Three seeding rates were planted under each irrigation level (low, medium and high), with four hybrids from each company (Pioneer and Syngenta). Pioneer provided three drought tolerant hybrids and one check hybrid. Syngenta provided one drought tolerant hybrid and three check hybrids. Plots were 10 feet wide and 40 feet long. Four replications of the Pioneer treatments were used and six replications of the Syngenta treatments were planted. Soil moisture was determined from core samples taken prior to planting and post-harvest. Irrigation scheduling was determined by using the Texas High Plains ET Network and plots were irrigated when soil moisture fell below 50% of plant available water (PAW) in the 100% ET irrigation level. Yields and grain moisture were determined by a Massey 8XP small plot combine with Alamco weigh scales. Biomass samples were harvested immediately after harvest, and then dried to determine biomass for harvest index (HI) calculations.

Principal Findings

- Surprisingly, all eight hybrids produced grain at the high population and lowest irrigation level (40% ET)
- Maximum water use efficiency (WUE) was observed at 75% ET with 40,000 seeds acre^{-1} at 8.64 bushels acre^{-1} inch^{-1} of total water. This supports previous research, that 75% ET has the highest WUE.
- Yield by population interactions were very much hybrid dependent. Complex interactions exist between water level, hybrid and yield exist in relation to plant population.

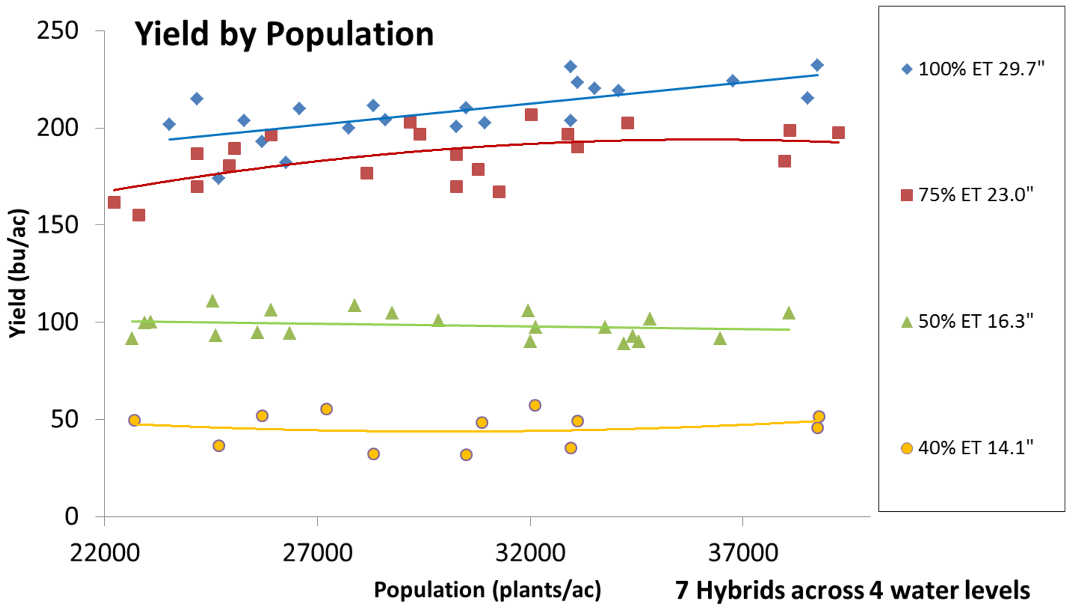


Figure 1. Yield by population across both trials

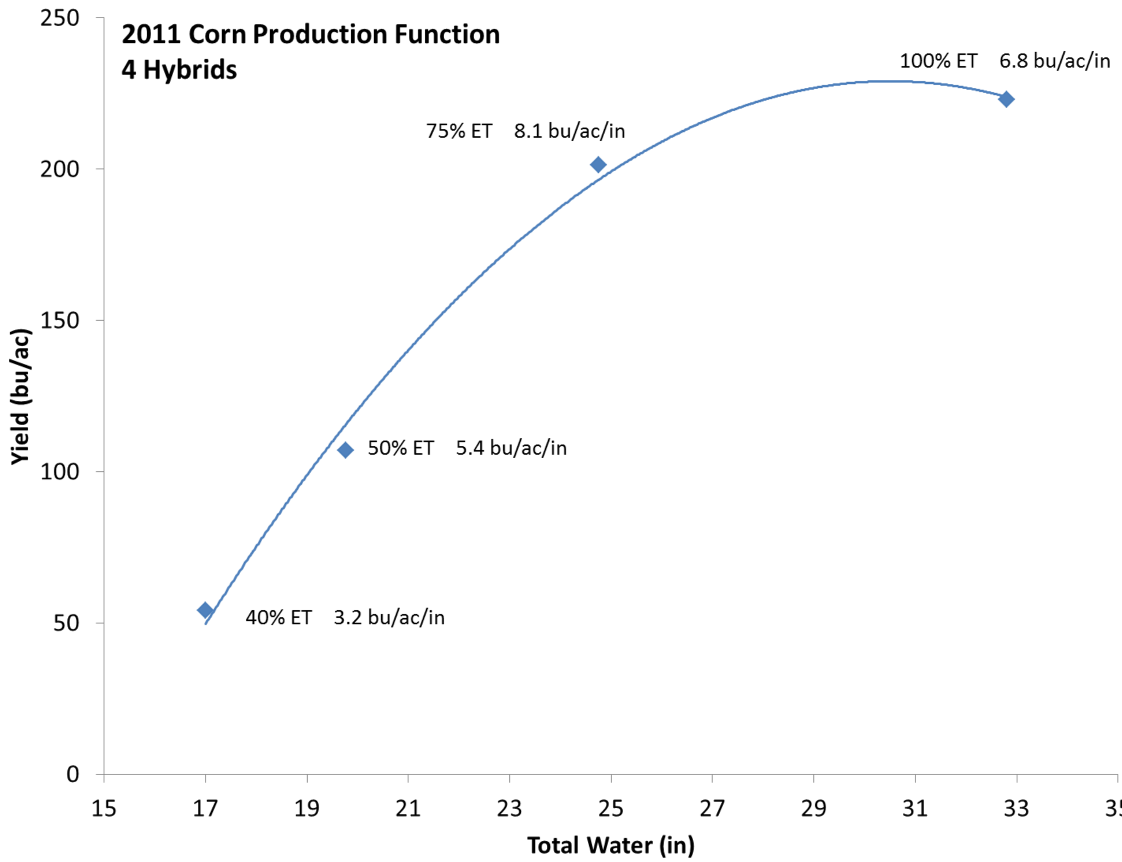


Figure 2. 2011 Production function. Notice steep curve at low water levels. Total water includes irrigation, soil water and rainfall.

- Yields were similar at low populations when comparing 100% and 75% ET irrigation levels (Fig. 1). This was caused by ears filling to the tip (maximum yield potential) at each water level.
- The production function is very steep at low water levels. At 40% ET, yields averaged 50 bushels per acre. At 50% ET, yields averaged 100 bushels per acre. There was only two inches difference in irrigation water and 50 bushels per acre difference in yield.
- In general, the drought tolerant hybrids did a better job pollenating and out yielded the check hybrids at lower irrigation levels.

Significance

The results of these studies provide the information necessary for understanding newly released hybrids and their relationship with irrigation water and plant population. Moving forward, limited irrigated corn will become a more normal production practice than fully irrigated corn. Results, such as these, can be used by regional producers and water districts on establishing obtainable yield goals with a set amount of irrigation water to pump. Drought tolerant corn hybrids will, without doubt, play a big role in producers' future production practices. All results from this study should keep in mind that the Texas Panhandle experienced exceptional drought and heat when this study was taking place.

Cotton-Biofuels Production Systems in a Changing High Plains Environment

Basic Information

Title:	Cotton-Biofuels Production Systems in a Changing High Plains Environment
Project Number:	2011TX391B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	19
Research Category:	Ecological Processes
Focus Category:	Agriculture, Groundwater, Irrigation
Descriptors:	None
Principal Investigators:	Cora Lea West Emerson, Dick Auld

Publications

1. Emerson, Cora Lea W., James P. Bordovsky and Dick L. Auld, 2012, Cotton-Biofuels Production Systems in a Changing High Plains Environment, Texas Water Resources Institute Annual Technical Report to U.S. Geological Survey, Texas A&M Univ., College Station, TX.
2. Emerson, Cora Lea W., James P. Bordovsky and Dick L. Auld, 2012, Cotton Production Systems in a Changing High Plains Environment, "in" Proceedings, 2012 Beltwide Cotton Conferences, National Cotton Council, Orlando, FL, pp. 206-12.

REPORT

Title: Cotton-Biofuels Production Systems in a Changing High Plains Environment

Project Number: 2011TX391B

Primary PI: Cora Lea W. Emerson

Other PIs: Dr. Dick L. Auld & James P. Bordovsky, P.E.

Abstract: Concern in the Texas High Plains over declining water tables has led local water conservation districts to impose increasingly restrictive pumping limits beginning in 2012. This, coupled with the increased need for dedicated crops to supply the region's confined animal feeding operations as well as support the state's push for biofuels production, and the issue of elevated cotton disease pressures will impact future production decisions. Traditionally, crop rotation systems in the region incorporate grain sorghum in rotation with cotton, which has been shown to reduce incidence of cotton disease; however, it has also been shown that such rotations do not compare favorably to continuous cotton either economically or in terms of water use efficiency. In 2011, a cotton–alternative crop rotation study was initiated on a 24-acre (9.7 ha) site at the Texas AgriLIFE Research Center in Halfway, Texas. While the overall objective of the study is to develop field data for eventual water policy and economic analysis; a first year objective was to establish a 2:1 cotton rotation system using two oilseed crops (sunflower and safflower), and two forage sorghum varieties in the rotation with cotton. The complementary objective was to document and compare water use and economic advantages/disadvantages among alternative crop cultivars versus continuous cotton where the primary water resource is rainfall supplemented by three very limited irrigation levels. The results showed that, in cotton, with 152 mm (6 in) of seasonal irrigation (High), yield, seasonal irrigation water use efficiency and irrigation water value was significantly greater than with 76 mm (3 in) of seasonal irrigation (Medium). In forage sorghum, at the High irrigation level, both total biomass and dry matter yield were significantly higher than at the Medium level; however, seasonal irrigation water use efficiency and irrigation water value were statistically ($\alpha = .05$) the same for each variety. For oilseed crops, no statistical differences were observed in any measured parameter between the High and Medium irrigation levels. Seed and oil yield were significantly lower in both sunflower and safflower at the Low (pre-plant only) irrigation level. Based on soil water monitoring, cotton depleted soil water by approximately 42 mm (1.67 in) over the growing season, while the alternative crops resulted in 63.5 mm (2.5 in) of soil water depletion. Among treatments for 2011, irrigation water value was highest where cotton was irrigated at the High level, having a relative value of $52.00/ac-in.

Problem and Research Objective: The Texas High Plains (THP) region has long faced the reality of declining water availability in the Ogallala and other minor panhandle aquifers. Storage in the southern region of the Ogallala Aquifer has declined from 500 billion m^3 in 1990 to approximately 436 billion m^3 in 2004, a 12% decline over the 15-year period (Ogallala Aquifer Maps, TTU-CGT); and, according to the 2007 State Water Plan, the volume of Ogallala water available for use in 2010 was 7 billion m^3 and will decline annually to 4.2 billion m^3 by 2060 (Water for Texas, 2007). The state's water policy is now aimed at reducing the rate of groundwater withdrawals. The Texas Water Code now requires groundwater conservation districts to develop each aquifer's "desired future conditions" within groundwater management areas to determine management goals for that aquifer, essentially regionalizing water management (TWC §35.004 *et seq*.). The code also requires a target and/or cap for groundwater permitting. To comply with the second requirement, THP water districts have implemented mandatory pumping limits, to be phased in over a four-year period beginning in 2012 (HPUWCD No. 1, 2012).

Also, there is an increased interest in biofuel production (*other than corn-based ethanol*) both at the state and federal levels. In 2009, the state legislature established the Texas Bioenergy Policy Council and Research Committee under the umbrella of the Texas Department of Agriculture. These bodies were charged with the task of developing strategies to further the state's goal of positioning itself as the nation's leader in bioenergy production by "*identifying strategies to the potential transition of agriculture in* ***western regions*** *of Texas to* ***dryland bioenergy crops*** *that are not dependent on groundwater resources*" (TDA, 2011). Meanwhile, federal mandates and incentives are also driving the expectation of major increases in the production of biomass (U.S. DOE, 2009). The federal Renewable Fuels Standard now requires 15.2 billion gallons of renewable fuel be produced in 2012 (U.S. EPA, 2012), and the Energy Independence and Security Act of 2007 sets the long-term production target at 36 billion gallons per year by 2022 (U.S. DOE, 2009).

Further, due to its environmental suitability, the THP has a very high concentration of confined animal feeding operations (CAFO). In 2011, there were 2.57 million head on feed for slaughter (85% of the state's total and 22% of the nation's total) in the THP, and the region is home to 8 of the state's top 10 dairy producing counties, producing 54% of the state's milk (USDA-NASS, 2011). These industries rely heavily on grains shipped from out of state; thus, there is a need for locally grown feeds to stay viable.

Finally, there is the growing issue of disease pressure in cotton monoculture: Verticillium wilt is the most yield-limiting cotton disease in the THP region and can drastically affect water use efficiency by reducing yield (Wheeler, *et al.*, 2009). In field tests at the Helms Research Farm in 2008 and 2009, the incidences of wilt in cotton were reduced from 30% to less than 8% by using sorghum every third year in rotation with cotton (Wheeler, *et al.*, 2009). While cotton crop rotation strategies in this region typically include cotton in rotation with grain sorghum; an 8-year cotton/grain sorghum study showed that rotation with grain sorghum did *not* favorably compare to continuous cotton either economically or from a water use efficiency perspective at current commodity prices (Bordovsky, *et al.*, 2011).

The foregoing issues will require area producers to consider alternatives to the traditional cotton production systems. Several crops have been identified as reasonable alternatives for rotation with cotton due to their adaptability to the region and potential value in the animal feed/bioenergy markets. These include the oilseed crops safflower and sunflower, as well as forage sorghums for animal feed or potential biomass conversion, among others. Each of these crops has been grown with varying levels of success in the region; although there are no known long-term studies documenting detailed water use and crop responses when incorporated in cotton rotation systems at extremely low irrigation levels.

The overall objective of this project is to document total water use and crop response in rotation systems where alternative crops are grown with cotton. Specific objectives are to: 1) establish a 2:1 cotton rotation using biofuels crops in the rotation; 2) begin documenting and comparing water use among rotation sequences versus continuous cotton where the primary water resource is rainfall supplemented by very limited irrigation; and 3) begin documenting crop yield and quality, nutrient use, pest and disease pressures and determining water use efficiency and economic advantages/disadvantages of alternative crops rotated with cotton compared to the traditional continuous cotton system.

Materials/Methodology: In 2011, a 2:1 cotton-alternative (AC) crop rotation study was initiated on a 9.7 ha (24-acre) field at the Texas AgriLIFE Research Center in Halfway, Texas. The study was established under an 8-span center pivot with crops irrigated by LEPA using circular rows oriented perpendicular to the pivot lateral. Rotation treatment plots included: cotton followed by cotton and then the AC treatment (**CCA**); cotton followed by AC and then cotton (**CAC**), and; AC followed by two years of cotton (**ACC**). The rotation treatments will be compared to continuous cotton (**CCC**). Rotation treatment areas were 16 1-m (40") rows wide and arced 180° of the pivot circle. The 180° pivot arc was divided into six pie-shaped wedges containing the irrigation treatments, where in-season irrigation was held to 0 mm or "pre-plant irrigation" only (**Low**); 76 mm (**Med.**), and 152 mm (**High**), respectively in each of two randomly selected wedges. Treatment plots were arranged in a randomized block design within 4 blocks. Plot sizes ranged from ~ 0.05 to 0.2 ha (.15 - .5 acres) allowing 4 alternative crops or varieties to be planted as sub-plots within the AC treatment areas. The field design and crop rotation sequence are shown in Figure 1, below.

The AC treatments consisted of: sunflower (Cruiser Maxx s668); safflower (TTU #1601), and; two sorghum/sudan-hybrid forage sorghum varieties (Maxi Gain BMR & Sugar Graze Ultra, Coffey Seed Co., Plainview, Texas). Sunflower and safflower crops were planted on 20-April at ~ 49,400 plants ha^{-1} (20,000 ppa) and ~ 226,000 plants ha^{-1} (91,500 ppa) respectively. Cotton (FM 9160 B2F) was planted 17-May at ~ 116,000 plants ha^{-1} (47,000 ppa), and the forage sorghum varieties were planted on 31-May at ~ 6.5 kg/ha (5.8 lbs/ac) and ~ 6.2 kg/ha (5.5 lbs/ac) respectively. All treatments were planted using a John Deere® Max Emerge planter.

Figure 2 shows the target and applied seasonal irrigation schedule for each crop. Target irrigation timing and amount were determined based on crop water use curves and known critical development periods for each crop. A Lindsay FieldBasic® programmable irrigation controller with electronic valve was used to pressurize the pivot, set the appropriate pivot speed, and stall/drain the pivot between irrigation treatments (wedges). Access tubes were placed to a depth of ~ 2 m (6.5') in the oilseed treatments, and ~ 1.4 m (4.5') in the forage sorghum and cotton treatments, and volumetric soil water content was monitored throughout the season in four replicates of each crop by the neutron scatter method, beginning 1-June and ending 27-September.

Safflower and Sunflower Sampling Methods

Representative samples (4 rows by ~ 4 m) from plots of the safflower and sunflower were hand-harvested on 25-July and 5-August respectively. Samples of each crop were threshed using a large plot thresher. Seed yield, water use efficiency (WUE), seasonal irrigation water use efficiency (SIWUE), and seasonal irrigation water value (SIWV) were determined from the resulting seed weights and harvest area for each crop, and oil and moisture content were determined by Nuclear Magnetic Resonance Spectrometry (NMR) analysis at the Texas AgriLIFE Research Seed Laboratory in Lubbock, Texas. Oil yield was determined for each crop based on NMR results.

Forage Sorghum Sampling Methods

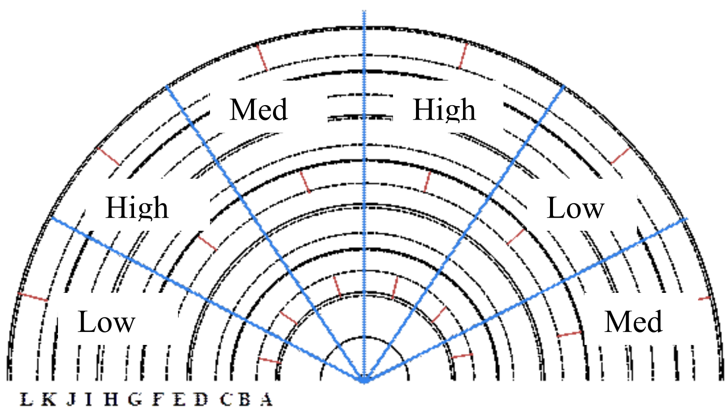
Representative samples (4 rows by ~ 4 m) from plots of the two forage sorghum varieties were hand-harvested on 19-September. Whole plants were weighed and chopped in the field using a 2" Cub Cadet® chipper/shredder to determine total biomass yield. Ensilage was hand-mixed and ~ .91 kg (2-lb) sub-samples were placed in a sealed container and immediately frozen. Forage quality for each replication and variety was determined from the frozen sub-samples by Near Infrared (NIR) analysis at an independent laboratory. Wet and dry yield, water use efficiency (WUE), seasonal irrigation water use efficiency (SIWUE), and seasonal irrigation water value (SIWV) were determined from the field weights and NIR results.

Cotton Sampling Methods

Cotton treatments were machine-harvested with a John Deere® 7445 stripper equipped with on-board scales and area calculator (Calc-An-Acre®), which recorded seed cotton weights and harvest distance at each sampling site. In 2011, samples were taken from each crop strip along the pivot lateral, and at each irrigation treatment along the pivot arc for a total of 54 samples. Approximately .45- to .91-kg (1 – 2 lb) sub-samples from each seed cotton sample were ginned at the Texas AgriLife Research and Extension Center's gin in Lubbock, Texas. Lint yield was determined using harvested area, seed cotton harvest weight and lint turnout percentage. Lint quality was determined by HVI analysis performed on all lint samples at the Fiber & Biopolymer Research Institute at Texas Tech University in Lubbock, Texas. Loan values were determined based on HVI results.

Calculations

WUE for each treatment and replicate was calculated by dividing lint yield (cotton), seed yield (oilseed) or dry yield (forage sorghum) by total in-season water (rainfall + in-season irrigation + change in soil water content). SIWUE was calculated by subtracting non-irrigated yield (Y_{DL}) from irrigated yield for each treatment (Y_P) and dividing the product by in-season irrigation (I_S), [$Y_P - Y_{DL}/I_S$]. SIWV ($/acre-in) was calculated by multiplying the crop price ($/lb) by SIWUE (lbs/acre-in). Crop prices for sunflower, cotton and forage sorghum (*i.e.* hay) were estimated from USDA-NASS United States/Texas average price received (projected) for November 2011 (USDA-NASS, 2011). The prices used were as follows: Texas average for sunflower ($18.70/cwt); U.S. average for Upland cotton ($.817/lb); and, U.S. average for "other" hay ($122.00/ton). Safflower price was estimated based on 2011 locally contracted price ($.20/lb). SIWV estimations did not account for input costs, premiums or discounts due to quality, or value-added products (*i.e.* milk production, safflower oil for consumption, or cottonseed value). Lint, seed/oil, and hay yield, cotton loan value, SIWV and SIWUE of the four replicates were averaged by treatment and comparisons made using standard analysis of variance with separation of means by Fisher's least significant difference method.



Block	Crop Strip	No. of Rows	Year 2011
1	A	16	ACC
1	B	16	CAC
1	C	12	CCC
1	D	16	CCA
2 & 3	E	16	CAC
2 & 3	F	16	ACC
2 & 3	G	12	CCC
2 & 3	H	16	CCA
4 & 5	I	16	CAC
4 & 5	J	16	CCA
4 & 5	K	12	CCC
4 & 5	L	16	ACC
Border		4	CCC

Figure 1. 2011 field design (9.7 ha), showing 3 irrigation treatments, and 12 crop strips (left); and, legend showing cropping sequences by block (right). Texas AgriLIFE Research Center - Halfway.

2011		High (6" In-season Irr.)								Med. (3" In-season Irr.)							
		Sorghum		Cotton		Sunflower		Safflower		Sorghum		Cotton		Sunflower		Safflower	
Irr. Week	Date	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*	*Tgt*	*Appl*
1	5-Jun		**1**			1	**1**	1	**1**		**1**			1	**1**	1	**1**
2	12-Jun					1	**1**	1	**1**					1	**1**	1	**1**
3	19-Jun	1		1	**1**	1	**1**	1	**1**				**1**	1	**1**	1	**1**
4	26-Jun					1	**1**	1	**1**						**0.5**		**0.5**
5	3-Jul	1	**1**	1	**1**	1	**1**	1	**1**	1	**1**	1	**1**				
6	10-Jul					1	**1**	1	**1**								
7	17-Jul	1	**1**	1	**1**					1	**1**	1	**1**				
8	24-Jul		**1**		**1**						**1**	1	**1**				
9	31-Jul	1		1						1							
10	7-Aug	1	**1**	1	**1**												
11	14-Aug	1	**1**	1	**1**												
12	21-Aug																
13	28-Aug																
Total		6	**6**	6	**6**	6	**6**	6	**6**	3	**4**	3	**4**	3	**3.5**	3	**3.5**

Figure 2. Target and applied seasonal irrigation schedule for cotton-alternative crop rotation study at Texas AgriLIFE Research Center-Halfway, 2011.

Principal Findings: Tables 1 through 4, below contain average yield, cotton loan value, WUE, SIWUE and SIWV for cotton and four alternative crops by irrigation level for 2011. In cotton (Table 1) a significant difference (α=.05) among irrigation levels was observed for yield, SIWUE and SIWV. In the two varieties of forage sorghum, while a significant difference in yield was observed among irrigation levels; there were no corresponding differences in SIWUE or SIWV (Table 2). In sunflower and safflower (Tables 3 & 4) there were no significant differences in yield, SIWUE or SIWV in the High versus Med. irrigation levels; however, a statistical difference was observed between the High versus Low irrigation levels in both crops.

Numerical differences were seen in yield, SIWUE and SIWV between the two forage sorghum varieties (Maxi Gain BMR being greater than Sugar Graze Ultra), as well as between the two oilseed crops (sunflower having the greater yield, SIWUE and SIWV compared to safflower). This was unexpected given that the sunflower experienced severe pest pressure from carrot beetle (*Tomarus gibbosus*) infestation, resulting in a high degree of crop loss.

Among all treatments, cotton irrigated at the High level resulted in the highest relative water value at $52.00/ac-in (Figure 3). Also, the average seasonal change in profile water for cotton was less than the alternative crops. The change in soil volumetric water content (Δ VWC) in cotton from 1-June through 27-September was approximately 1.67 inches (42.4 mm), while the alternative crops approached 2.5 inches (63.5 mm). This value represents the average at all irrigation levels. As shown in the figure, under conditions such as those experienced in 2011, cotton resulted in the highest water value with the least seasonal soil water depletion.

Table 1. Average lint yield (lbs/ac), loan value ($/lb), SIWUE (lbs/ac-in), SIWV ($/ac-in), and WUE (lbs/ac-in) in cotton at three irrigation levels. Texas AgriLIFE Research Center at Halfway, Texas, 2011.

Irr. Level	Avg. Lint Yield (lbs/ac)	Avg. Loan Value	Avg. SIWUE (lbs/ac-in.)	Avg. SIWV ($/ac-in.) @ .82/lb	Avg. WUE (lbs/ac-in.)
High (6")	504[A]	0.51[A]	64[A]	52[A]	50[A]
Med. (4")	269[B]	0.47[A]	38[B]	31[B]	33[B]
Low (PP)	119[C]	0.51[A]			29[B]

Means with the same letter are not significantly different (Fisher's LSD method; α=.05).

Table 2. Average wet yield (lbs/ac), dry yield (lbs/ac), SIWUE (lbs/ac-in), SIWV ($/ac-in), and WUE (lbs/ac-in) in two forage sorghum varieties at three irrigation levels. Texas AgriLIFE Research Center at Halfway, Texas, 2011.

Irr. Level	Avg. Wet Yield (lbs/ac)	Avg. Dry Yield (lbs/ac)	Avg. SIWUE (lbs/ac-in.)	Avg. SIWV ($/ac-in.) @ $122/ton	Avg. WUE (lbs/ac-in.)
Maxi Gain BMR					
High (6")	15594[A]	3854[A]	534[A]	33[A]	321[A]
Med. (4")	9997[B]	2749[B]	525[A]	32[A]	275[AB]
Low (PP)	4480[C]	1335[C]			223[B]
Sugar Graze Ultra					
High (6")	17139[A]	4550[A]	648[A]	40[A]	379[A]
Med. (4")	11487[B]	3251[B]	647[A]	39[A]	325[A]
Low (PP)	4480[C]	1364[C]			228[B]

Means with the same letters are not significantly different (Fisher's LSD method; α=.05).

Table 3. Average seed yield (lbs/ac), oil yield (lbs/ac), SIWUE (lbs/ac-in), SIWV ($/ac-in), and WUE (lbs/ac-in) in sunflower at three irrigation levels. Texas AgriLIFE Research Center at Halfway, Texas, 2011.

Irr. Level	*Avg. Seed Yield (lbs/ac)	Avg. Oil Yield (lbs/ac)	Avg. SIWUE (lbs/ac-in.)	Avg. SIWV ($/ac-in.) @ $18.70/cwt	Avg. WUE (lbs/ac-in.)
High (6")	**804[A]**	**327[A]**	**67[A]**	**12[A]**	**78[A]**
Med. (3.5")	**567[AB]**	**238[AB]**	**52[A]**	**9[A]**	**73[A]**
Low (PP)	**334[B]**	**152[B]**			**79[A]**

**8% moisture.*

Means with the same letters are not significantly different (Fisher's LSD method; α=.05).

Table 4. Average seed yield (lbs/ac), oil yield (lbs/ac), SIWUE (lbs/ac-in), SIWV ($/ac-in), and WUE (lbs/ac-in) in safflower at three irrigation levels. Texas AgriLIFE Research Center at Halfway, Texas, 2011.

Irr. Level	*Avg. Seed Yield (lbs/ac)	Avg. Oil Yield (lbs/ac)	Avg. SIWUE (lbs/ac-in.)	Avg. SIWV ($/ac-in.) @ .20/lb	Avg. WUE (lbs/ac-in.)
High (6")	**547[A]**	**197[A]**	**33[A]**	**7[A]**	**53[A]**
Med. (3.5")	**480[A]**	**169[A]**	**36[A]**	**6[A]**	**62[A]**
Low (PP)	**245[B]**	**86[B]**			**58[A]**

**4.5% moisture.*

Means with the same letters are not significantly different (Fisher's LSD method; α=.05).

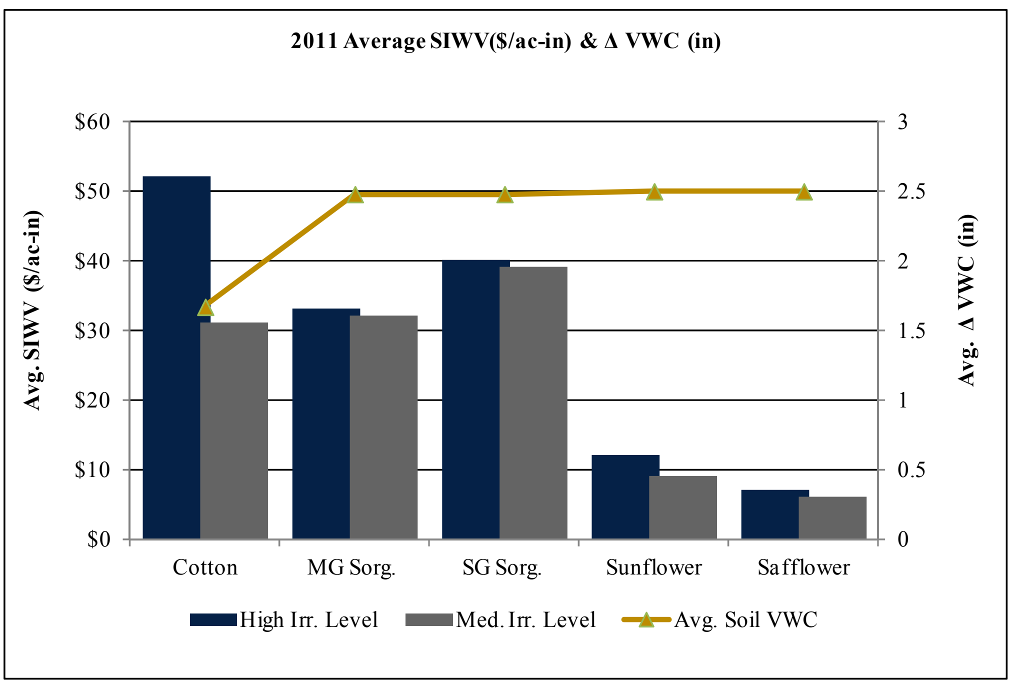


Figure 3. Relative seasonal irrigation water value ($/ac-in) and average seasonal change in soil volumetric water content (in) in cotton and four alternative crops at High and Med. irrigation levels. Texas AgriLIFE Research Center at Halfway, Texas, 2011.

Significance: While these initial data are useful for a cursory evaluation of the feasibility of cotton-alternative crop systems, the ultimate goal of this study is to develop a dataset for comprehensive economic/policy analysis of Texas High Plains cropping systems under severe irrigation limits. This report describes the first year of the study. The 2011 growing season was characterized by severe drought and unusually high temperatures, with 2011 being both the driest and hottest year on record for the region. These conditions contributed to atypical yield results, even for those crops considered to be drought tolerant. As one would expect in a dry year, yields were significantly increased by increases in irrigation level. The highest seasonal irrigation water value ($52.00/ac-in) among all crops was in cotton at the High irrigation level. This suggests that when water is severely limited, the better production decision may be to reduce input costs by planting cotton on a smaller area and irrigating at a higher rate compared to other alternatives.

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Emerson, Cora Lea W., James P. Bordovsky and Dick L. Auld, 2012, Cotton-Biofuels Production Systems in a Changing High Plains Environment, *Texas Water Resources Institute Annual Technical Report to U.S. Geological Survey*, Texas A&M Univ., College Station, TX.

Emerson, Cora Lea W., James P. Bordovsky and Dick L. Auld, 2012, Cotton Production Systems in a Changing High Plains Environment, *"in" Proceedings, 2012 Beltwide Cotton Conferences*. National Cotton Council, Orlando, FL, pp. 206-12.

Landscape Coefficients in Mixed Species Landscapes

Basic Information

Title:	Landscape Coefficients in Mixed Species Landscapes
Project Number:	2011TX392B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	8
Research Category:	Ecological Processes
Focus Category:	Conservation, Irrigation, None
Descriptors:	None
Principal Investigators:	Rebecca Hammond, Tim Pannkuk

Publications

There are no publications.

Title- Landscape Coefficients in Mixed Species Landscape

Project Number- 2011TX392B

Primary PI- Rebecca Hammond, M.S.

Other PI- Tim Pannkuk, Ph.D.

Abstract- Combinations of landscape plants were used to measure crop coefficients (K_L). This was measured as the amount of water used by the crops actual evapotranspiration (ET_A) and compared to that of reference evapotranspiration (ET_o). Irrigation was based on 100% replacement of ET_o. The K_L values were determined using the following landscape crops: St. Augustinegrass, Burford Holly, Yaupon Holly, Ligustrum and Loropetalum. The plants were planted in lysimeters with the dimensions of 2.1 m long x 1.2 m wide x 0.6 m deep. Each lysimeter has six soil moisture probes that took measurements at depths of 0 to 20, 20 to 40, and 40 to 60 cm. The lysimeters contained a PVC leachate pipe system to vacuum leachate out of the lysimeters. The lysimeters were irrigated every 4 to 7 days with a sprinkler system in the event of no precipitation. The K_L for spring 2012 ranged from .67 to 1.06. The average leachate depth for the same time period ranged from 21.3 to 25.6 mm. Landscape coefficients can be used when making irrigation decisions for all landscape purposes.

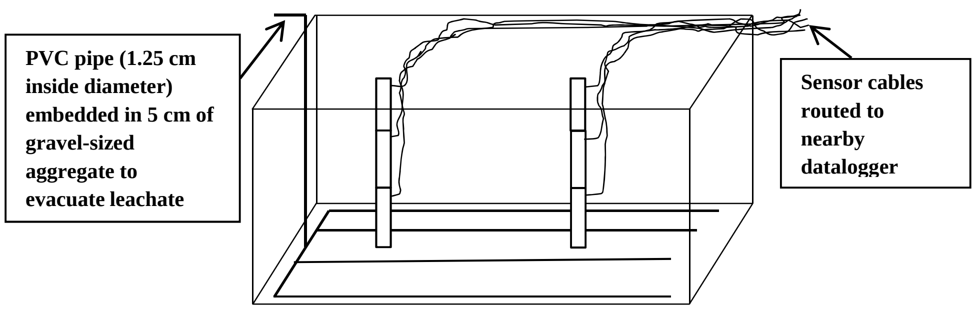
Problem and Research Objectives- Water used for landscape irrigation purposes has become a major issue with conservationists. The objective of this experiment is to use the seasonal water uptake of landscape crop within the lysimeters to calculate actual evapotranspiration (ET_A) and compare to the reference evapotranspiration (ET_o) data that will be collected from the weather station at Sam Houston State University.

Materials/Methodology- The experiment was conducted at the Sam Houston State University Horticulture Center. Irrigation water was supplied from Huntsville Municipal Water Supply. A water analysis was performed in June of 2011, and a soil analysis was performed in June of 2011.

Lysimeter construction. The lysimeter dimensions are 2.1 m L x 1.2 m W x 0.6 m D. An EPDM landfill liner was placed along the bottom and sides of the lysimeters leaving a 5.1 cm border around the top to collect the rainfall within the lysimeters. A 5.1 cm layer of 0.95 cm gravel was placed on the bottom of each lysimeter. A PVC leachate pipe system was constructed and placed in this gravel to allow removal by vacuum. The leachate pipe system consisted of four long pieces manifolded together to a riser at one end. Each lateral piece had holes drilled into it every six inches on the bottom side to allow water to enter the pipes. Each lateral pipe was capped.

The soil was sifted through a screen before being added in lifts of six inches and hand tamped down to four inches. This was repeated until the lysimeters were 2 inches above the surrounding ground level. There were six soil moisture probes placed on the east and west side of each lysimeter. The probes were Decagon 10HS (Decagon Devices, Pullman, WA). The sensors measured soil moisture at 0 to 20, 20 to 40, and 40 to 60 cm depths. The cables from the sensors were routed along the side of the lysimeters, through a trench and connected into a multiplexer which was wired into a data logger (Fig. 1).

Fig. 1



Lysimeters were irrigated manually with an in-ground sprinkler system and a water meter was installed to measure the amount of water applied. A weather station at the Horticulture Center that is located approximately 50 m from the lysimeters. ET was calculated from this weather station and the irrigation schedule would be determined weekly. The irrigation was to replace 100% of the ET_o minus rainfall.

Plant Installation- Lysimeters were arranged in a randomized complete block design with three replications. The plants included: St. Augustinegrass, Loropetalum, Ligustrum, Burford Holly and Yaupon Holly. Plant installation occurred in May 2011. Treatments are a combination of turfgrass and woody plants at the following ratio of plant cover: 20% turf/ 80% woody, 50% turf/ 50% woody, and 80% turf/ 20%woody. The St. Augustinegrass was mowed at a height of 2-3 inches depending on the season. The lysimeters were evacuated once a week with a ½ horsepower electric pump. The pump was fitted with a tube that connected to the glass carboy with a rubber stopper in the opening. An additional tube came out of the rubber stopper and connected to the riser in the lysimeter. The amount of water that was evacuated from each lysimeter was measured and a sample was taken and frozen for later observation.

Principal Findings- During the summer of 2011, Texas experienced a state wide drought. Unusually high temperatures that season slowed the establishment period for the landscape crops. Some plants needed to be replaced, thus extending the establishment period.

During the Spring of 2012, the K_L was greater for the higher woody plant and low turf percentage. K_Ls are as follows: 20% turf/ 80% woody plant was 1.06, 50% turf/ 50% woody plant was .80 and 80% turf/ 20% woody plant was .67. For the same time period, the leachate volume for the treatment with the lowest woody percentage had the highest leachate collection average. The leachate depth averages are as follows: 20% turf/ 80% woody plants was 4.7 mm, 50% turf/ 50% woody plants was 7.3 mm, and 80% turf/ 20% woody plants was 8.3 mm.

Significance- Results indicate that treatments with higher percentage of woody plants have a higher K_L and use more water. The results also indicate that treatments with a higher turf percentage will leach water more quickly and have a lower K_L. This is a strong indication of landscapes that are mostly turf having the ability to leach more water into the ground water and help recharge aquifers. Water districts and water purveyors can use this information within their districts to create and maintain a water usage program. This information can also help environmentally conscious land owners make informed decisions on landscaping and water use. Also because of these results, communities and neighborhoods with homeowner’s associations can create a law or act that requires or denies specific plants for the surrounding landscape.

Reusable Magnetic Janus Particle Scavengers for Environmentally-Friendly Remediation of Contaminated Water Bodies

Basic Information

Title:	Reusable Magnetic Janus Particle Scavengers for Environmentally-Friendly Remediation of Contaminated Water Bodies
Project Number:	2011TX393B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	17
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Toxic Substances, Water Quality
Descriptors:	None
Principal Investigators:	Nina Ivanova, Nicole Zacharia

Publications

1. Ivanova, Nina, and Nicole Zacharia, 2012, Patchy Particle Synthesis via Capillary Condensation, Colloids and Interfaces B, submitted.
2. Ivanova, Nina, 2011, Improved Synthetic Methods for Patchy Particles, M.S. Dissertation, Mechanical Engineering, College of Engineering, Texas A&M University, College Station, TX, 75 pages.
3. Ivanova, Nina, Chungyeon Cho, Prasenjit Kar, and Nicole Zacharia, 2012, Reusable Magnetic Janus Particle Scavengers for Environmentally Friendly Remediation of Contaminated Water Bodies, Texas A&M University, College Station, TX, 7 pages.

REPORT

Title Reusable Magnetic Janus Particle Scavengers for Environmentally Friendly Remediation of Contaminated Water Bodies

Project Number 2011TX393B

Primary PI Nina Ivanova,* Chungyeon Cho
*N. Ivanova was supported for the first 3 months on this grant until her graduation

Other PIs Prasenjit Kar, Nicole S. Zacharia

Abstract:

Industrial waste containing petroleum products and heavy metals, as well as concern over the fate of oil released from the recent BP Deepwater Horizon rig accident are problems facing the Texan water supply that need to be addressed. One concern with adding small molecule surfactants to the water supply to disperse oil spills or other hazardous materials is the ultimate fate of those small molecules. One proposed solution to this is the fabrication of a retrievable particle for the same purpose. The Janus particle, a compartmentalized colloidal particle with two chemically or physically different sides, can form stable emulsions that can entrap oil or heavy metals depending on the ligands attached to the particle. The emulsion can consequently be destabilized by application of a magnetic field which will allow recovery and recycling of the particles and collection and disposal of oil or heavy metals. Over the course of the sponsored research we have developed solution synthesis for Janus partiles with different functionalities as well as a synthesis for core-shell magnetic nanoparticles. Future work will include the combination of these materials.

Problem and Research Objectives:

Oil refineries, pipe-lines and off-shore drilling pose an increased risk to the water supply of the state of Texas. The recent explosion of BP Deepwater Horizon rig released 4,928,100 barrels of oil from the Macondo well into the Gulf of Mexico with an error margin of 10% (1). While a large portion of this oil has been recovered or eliminated, 1,281,306 barrels, or 26% of the total amount (1), is unaccounted for and could potentially wash ashore, contaminating estuaries and wetlands. Marsh cleanup is often suggested as a way to prevent oiling of birds or other animals and to prevent oil from moving to nearby environments (2). Run-off from oil refineries, heavy metal contained in industrial waste and non-point pollution are also an increasing threat to the quality of Texan water supply, and different methods have been used to remedy these problems, one of them being surfactants.

Addition of surfactants, molecules containing a hydrophobic and hydrophilic end, is a common way to approach oil spill and other toxic waste remediation. In the case of oil, surfactant molecules create stable emulsions of non-polar oil constituents by forming micelles that render them water-soluble for easy removal. While introduction of biologically-derived surfactants in recent years helped address some of the concerns regarding environmental toxicity, the inability to recover and recycle surfactant at the end of an operation is still a problem. We propose using Janus particles, or functionalized colloidal particles, to address this issue due to their increased emulsifier potential and possibility of reuse and recycling.

Janus particles are compartmentalized colloidal particles with two sides of different chemistry or polarity (3). It is well-known that small particles can stabilize immiscible liquids forming so-called Pickering emulsions. Unlike surfactants, colloidal particles create more stable emulsions since more energy is required to remove them from the interface (4). Better yet, Janus particles offer a 3-fold emulsifier potential for water-oil emulsions over homogeneous colloidal particles in theoretical studies (5). We will use iron oxide-based particles due to their superparamagnetic properties, along with low cytotoxicity and colloidal stability for environmental advantages (6). Once the oil has been emulsified by the Janus particles and removed from the environment, a simple application of a magnetic field will align the particles into chains or clusters, which will disrupt the emulsion to allow collection of oil and recycling of the Janus particles.

Our long term objectives are to create Janus particles by immobilizing silica-coated magnetite colloidal particles at liquid paraffin/water interface via paraffin solidification and use aqueous/organic chemistry to modify first one, and then the other half of the exposed particles. Different ligands can be attached to the particle surface, and the functional group, length of ligand backbone and pH will influence the ultimate polarity and charge of the particle surface. The attached ligands can also have chelating properties, which can be used to complex and recover toxic heavy metals. The materials synthesis was divided into two parts; the Janus particle synthesis and the synthesis of the core/shell magnetic particles. Core/shell particles with a magnetite core and a silica shell are desired because the silica surface can be more readily modified than magnetite. Also, magnetite nanoparticles are smaller than the optimal particle size, and with the core/shell synthesis

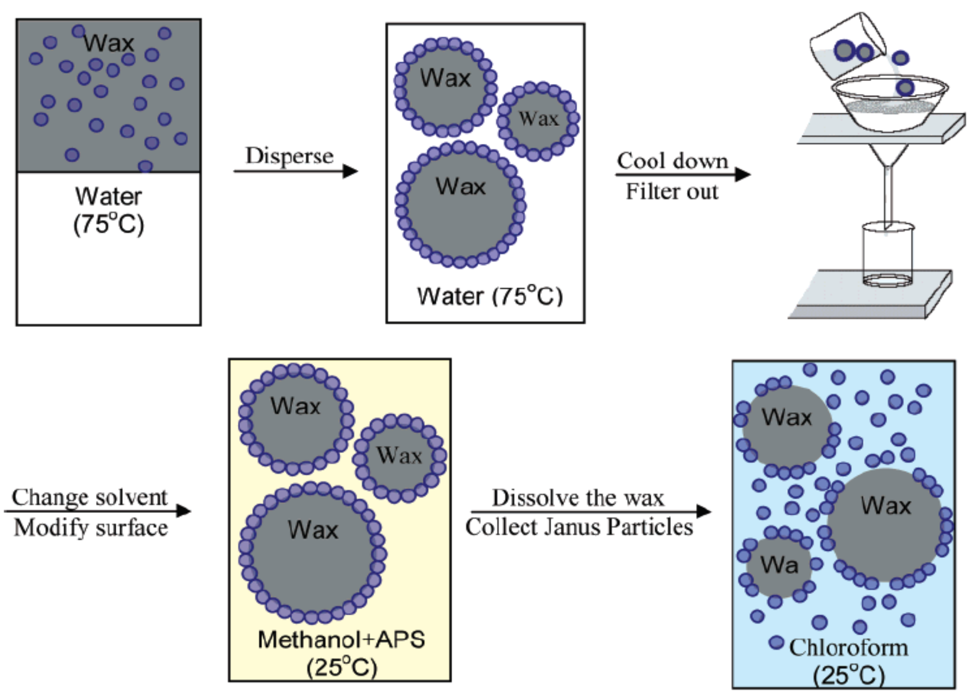


Figure 1: Schematic process of Janus particle synthesis. A wax drop in water immersion is formed, nanoparticles are assembled at the surface of these drops, which then serve to mask one side of the nanoparticles.

several magnetic nanoparticles are combined into one core to make an overall larger particle.

One of the problems in the field of Janus particle research is in creating a high yield high synthesis process for their fabrication. We have been working on a synthetic method based on the work of Granick, et al, schematically shown in figure 1 (7). In this method nanoparticles are assembled at the surface of larger wax droplets, which act as a mask to allow one side at a time to be functionalized. In order to characterize the Janus particles their assembly at organic/inorganic interfaces has been observed, and will continue to be observed in future work. Visual observation, rheological changes, sensitivity to turbulence and zeta potential of the emulsion over time, temperature, concentration and pH range are all techniques used for characterization.

Materials/Methodology

All chemicals were purchased from Sigma Aldrich and used without further purification.

Silica nanoparticles were synthesized with a modified Stober method as according to reference 8.

For the Janus functionalization of the silica nanoparticles paraffin wax and dried silica nanoparticles are added to water at 70°C and sonicated with a probe sonicator to form a good wax in water emulsion. When the emulsion is formed, the temperature is lowered and then the emulsion is filtered to separate thw wax particles from the water. These wax particles are redispersed in a methanol solution of silane of choice to modify the exposed particle surface. Dichloromethane is then added to dissolve the wax and release the Janus particles. Characterization was performed via SEM imaging and Zeta potential measurements.

For the magnetite nanoparticles, iron acetate, 1,2-hexadecanediol, oleic acid, and oleyl amine were mixed and stirred (8). The mixture was heated to 200 °C and then refluxed for an hour. Under ambient conditions, ethanol was added to the mixture and a black material was precipitated and separated via centrifugation.

Principal Findings

Our group has developed expertise in synthesizing monodisperse (within %5) silica spheres of different sizes. This was our starting point for developing Janus functionalization of these spheres with a solution state synthesis. The method is to create a wax in water emulsion (the wax droplets are large, hundreds of microns) and then allow the smaller particles of interest (e.g. silica spheres) assemble at the interface, shown in figure 5. The solution is then frozen and filtered, retrieving wax particles with smaller silica spheres embedded on the surface. These wax particles are redispersed and functionalization of the unprotected surface only is possible. Figure 2 shows SEM images of the surface of wax droplets with silica nanoparticles embedded in them. This demonstrates that A simple silanization imparts a different charge or other property to one side of the spheres. Then once the wax is dissolved the unfunctionalized side of the spheres can be functionalized. As an initial trial to begin optimization of this process, aminopropylsilane and octadecyltrichlorosilane were chosen for hydrophilic and hydrophobic functionalizations, respectively. Once Zeta potential measurements confirmed that these funcationalizations had worked, polyelectrolytes were chosen. We successfully functionalized Janus particles to have one hydrophobic face and one charged polyelectrolyte face,

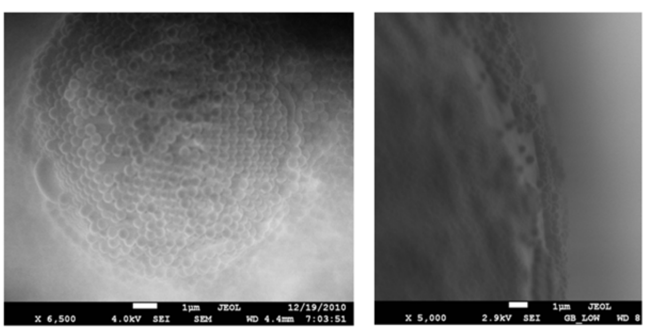


Figure 2: SEM images showing silica particles embedded in the surface of solid wax drops.

either negative or positive. Figure 3 shows the complexation of oppositely charged particles. This demonstrates our control of either face of the Janus particles.

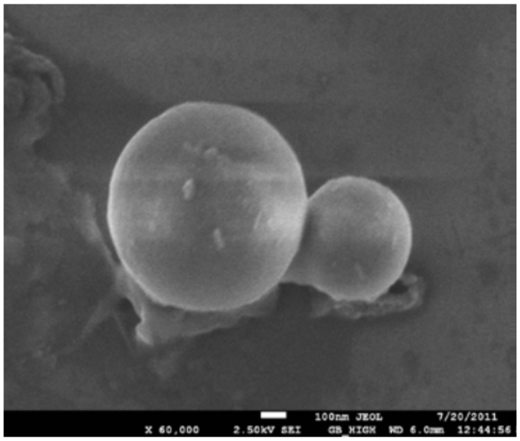


Figure 3: Doublet particles formed from the complexation of oppositely charged Janus particles.

Preliminary results show that the particles are more effective at stabilizing a water/toluene mixture than sodium dodecyl sulfate (SDS). Figure 5 shows time lapse images of water and toluene alone (first row), water and toluene with SDS (second row), and water and toluene with an equal wt% of functionalized 400 nm spheres (third row). All three mixtures were initially sonicated to create the dispersion, which explains why the water and toluene mixture doesn't separate more quickly. It can be seen that the unstabilized dispersion separates the most quickly, followed by the surfactant stabilized emulsion, followed by the particle stabilized emulsion. While there is still a great deal of work to be done investigating the effect of particle size and specific ligands used to impart hydrophobicity or hydrophilicity, we have shown that the Janus particles have potential to improve micellization over small molecule surfactants.

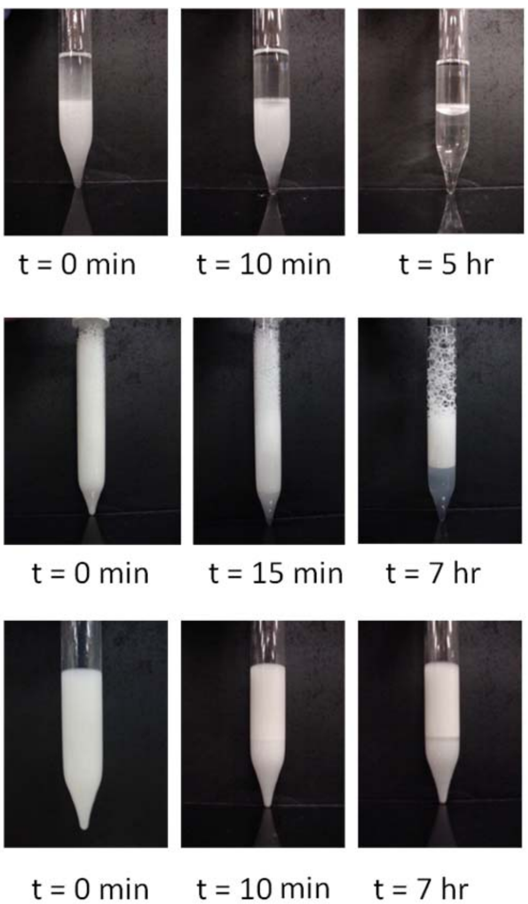
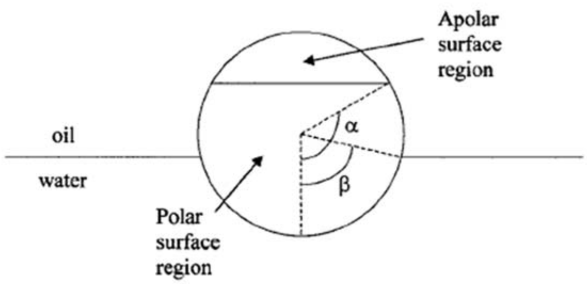


Figure 4: Top row shows the separation of water and toluene. Middle row shows the separation of the same but stabilized by 0.67 wt% SDS. Bottom row shows the separation of water and toluene stabilized by functionalized silica particles.

To demonstrate that our functionalized 400 nm particles are well adhered to the oil/water interface, figure 5 shows particles that are stabilizing a dichloromethane/water dispersion, and then after centrifugation for 30 min at 5000 rpm. While non-functionalized spheres would sediment under these conditions, it can be seen that the Janus particles adhere to the interface. The energy required to remove these particles from the interface is large.

In addition to development of the Janus functionalization, our group is working on core-shell colloidal particles with a magnetite core. If we can make particles with a magnetite core and a silica or gold shell, they will be retrievable by magnetic field but the surfaces will also be easily functionalized with either silanes or thiols. Figure 6 shows pictures of magnetite particles suspended in water (a) being attracted to a magnet and (c) SEM images of the same particles. The next steps towards making the core/shell particles involves coating these nanoparticles with a polymer ligand, which we have successfully accomplished, and then attaching silica seeds to the polymer surface.



Geometry of a Janus particle within an oil-water interface.

α – position of surface boundary between apolar and polar regions of particle.

β - immersion depth of the particle.

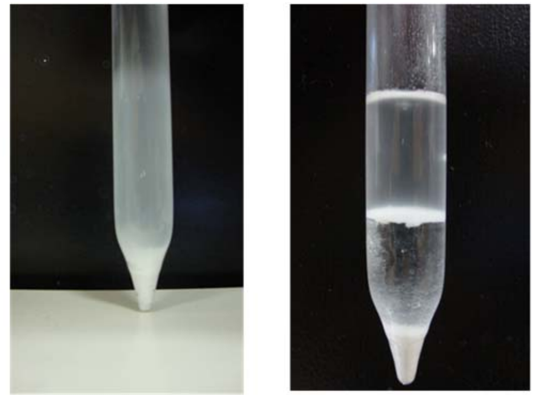


Figure 5: A schematic showing the geometry of how a Janus particle would sit at an oil/water interface,[16] and 400 nm Janus particles in an oil/dichloromethane dispersion. Even after 30 minutes of centrifugation at 5000 rpm, the majority of the particles stay at the interface and do not sediment.

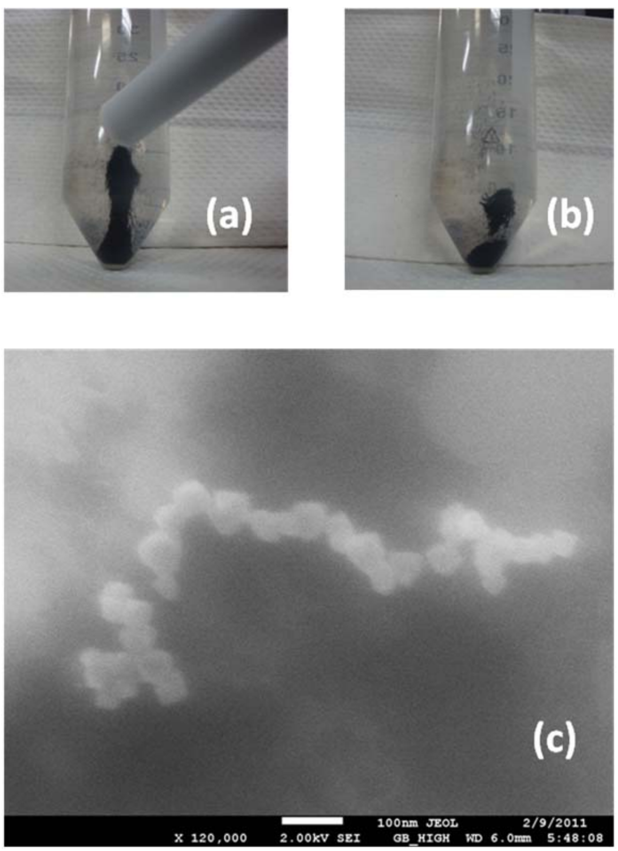


Figure 6: (a) Magnetite particles in water beingattracted by a magnet and (b) the same particles falling back down in the test tube after the magnet is removed. (c) SEM image showing that the particles are about 50 nm in size.

Significance

Over the course of the project, we have made significant gains towards optimizing the functionalization of Janus particles in solution. Our highest scale synthesis has been at the gram level, which is very important for any potential use of these materials. We are able to selectively functionalize one face with either small molecules or polymers. These particles are effective at the stabilization of oil/water interfaces. Future work includes more detailed studies of their assembly at oil/water interfaces.

We are able to successfully synthesize magnetic nanoparticles, and are working on the synthesis of core-shell particles based on these.

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1. Articles in Refereed Scientific Journals

Ivanova, Nina, Nicole Zacharia, 2012, “Patchy Particle Synthesis via Capillary Condensation,” Colloids and Interfaces B, submitted.

2. Dissertations

Ivanova, Nina, 2011, Improved Synthetic Methods for Patchy Particles, "M.S. Dissertation," Mechanical Engineering, College of Engineering, Texas A&M University, College Station, TX, 75 pages.

3. Water Resources Research Institute Reports

Ivanova, Nina, Chungyeon Cho, Prasenjit Kar, Nicole Zacharia, 2012, Reusable Magnetic Janus Particle Scavengers for Environmentally Friendly Remediation of Contaminated Water Bodies, Name of WRRI, Texas A&M University, College Station, TX, 7 pages.

Effect of Treatment on Harvested Rainwater Quality

Basic Information

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Principal Investigators:	Sarah Keithley, Mary Jo Kirisits

Publications

1. Keithley, Sarah, 2012, The effect of treatment on the quality of harvested rainwater, "MS Thesis," Environmental and Water Resources Engineering, Cockrell School of Engineering, The University of Texas, Austin, Texas, 119.
2. Keithley, Sarah, Mary Jo Kirisits, and Kerry Kinney, 2012, The effect of treatment on harvested rainwater quality, Texas Water Resources Institute, College Station, Texas, 4.
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USGS Program Report
Project Number: 2011TX394B

The Effect of Treatment on Harvested Rainwater Quality

Primary PI: Sarah Keithley
Other PIs: Dr. Mary Jo Kirisits and Dr. Kerry Kinney

May 2012

Executive Summary

Introduction

Rainwater is an alternative water resource that is receiving increasing attention as the demand for fresh water increases globally. Many studies have found the physical and chemical qualities of harvested rainwater to be satisfactory, but the microbial quality is often lacking (Jordan *et al.*, 2008; Despins *et al.*, 2009; Mendez *et al.*, 2011). If properly treated, harvested rainwater can be used as a local potable water supply. Our study investigated the effect of two treatment systems on the quality of harvested rainwater: (1) chlorination followed by filtration, and (2) filtration followed by ultraviolet (UV) irradiation.

Chlorine is a common disinfectant, but it reacts with natural organic matter to produce disinfection byproducts (DBPs) that can be carcinogenic or genotoxic (as reviewed by Richardson *et al.*, 2007). Rook (1974) identified trihalomethanes (THMs) as the first group of chlorine DBPs. The United States Environmental Protection Agency (USEPA) regulates total THMs (TTHM), which is the sum of four THMs; the maximum contaminant level (MCL) is 80 μg/L (USEPA, 2012). One study found that THM formation in chlorinated harvested rainwater was below the USEPA MCL (Lantagne *et al.*, 2008).

UV irradiation is becoming increasingly popular in the United States among rainwater harvesters (Macomber, 2010). Filtration is an important part of UV treatment systems since particles disrupt UV by absorbing UV light and shielding microorganisms (Qualls *et al.*, 1983). Previous studies have found UV irradiation to be a suitable method for disinfection of harvested rainwater (Jordan *et al.*, 2008; Despins *et al.*, 2009; Ahmed *et al.*, 2012).

While the discussion of the results references drinking water standards set by the United States Environmental Protection Agency (USEPA), those standards only apply to public water systems, i.e., systems with more than 15 connections or regularly serving more than 25 individuals. Rainwater harvested for individual potable use at a residence does not have to comply with USEPA regulations, but these standards provide a quality benchmark.

Chlorination Studies

For the chlorination studies, rainwater was harvested from four pilot-scale roofs in Austin, Texas. Each has a different roofing material, which are concrete tile, green, Galvalume® metal, and asphalt-fiberglass shingle. Mendez *et al.* (2011) previously characterized the quality of raw rainwater harvested from these same roofs. The harvested rainwater was allowed to settle at 4 °C for at least 12 h, and then the siphoned supernatant was used in experiments. Bleach was added to the harvested rainwater to achieve a target chlorine residual of 2 or 0.2 mg/L at 10 min after chlorination. The chlorinated rainwater was kept in a headspace-free polypropylene tank for 24 h. The residual chlorine concentration and THM concentrations were measured 10 min, 2, 4, 8, 12, 18, and 24 h after chlorination. At 24 h, chlorinated rainwater was pumped through a carbon block filter with a nominal pore size of 0.5 μm, and the THM concentrations in the filtered water were measured. Total coliforms (TCs) and heterotrophic plate counts (HPCs) were measured in the raw water and measured after chlorination and chlorination/filtration at 24 h.

The physical and chemical qualities of the rainwater harvested from the pilot-scale roofs were similar to those measured previously by Mendez *et al.* (2011), and TCs were detected in the raw harvested rainwater in most rain events. Disinfection efficacy and THM formation were compared among roofing materials after a 24-h contact time; the type of roofing material, dissolved organic carbon (DOC) concentration, and pH of the rainwater affected disinfection efficacy and THM formation. Adequate disinfection of rainwater was defined as the TC concentration being less than 1 colony forming unit per 100 mL (CFU/100 mL) and the TTHM concentration less than 80 μg/L (USEPA, 2012).

Chlorinating rainwater harvested from the metal roof achieved adequate disinfection, regardless of the targeted 10-min chlorine residual, and TTHM formation was well below the USEPA limit of 80 μg/L. The low DOC concentration and low pH of rainwater harvested from the metal roof likely contributed to the adequacy of chlorine as a disinfectant for this rainwater. Rainwater harvested from the concrete roof was of similar quality to rainwater harvested from the metal roof, and a target 10-min chlorine residual of 2 mg/L achieved adequate disinfection with TTHM formation below the USEPA limit. Chlorinating rainwater harvested from the shingle roof achieved adequate disinfection when the target chlorine residual was 2 mg/L, but the TTHM concentration exceeded the USEPA limit in one instance. The DOC concentration in rainwater harvested from the shingle roof differed by almost an order of magnitude among rain events, and this variability likely led to variable THM formation. This rainwater demonstrated that there is a balance between disinfection efficacy and DBP formation. Chlorination did not adequately disinfect rainwater harvested from the green roof, regardless of the targeted chlorine dose. The TTHM concentration was 4 times higher than the USEPA limit of 80 μg/L when the target 10-min residual was 2 mg/L, but was below the MCL when the targeted 10-min residual was 0.2 mg/L. Rainwater harvested from the green roof had the highest DOC concentration, which likely limited disinfection and led to high THM formation. Chlorine did not appear to be a good disinfectant for rainwater harvested from the green roof.

The activated carbon block filter used after chlorination reduced the TTHM concentration to well below the MCL, regardless of the influent TTHM concentration, but it often shed heterotrophic bacteria and TCs. Rainwater harvesters who chlorinate their rainwater often use a carbon filter after chlorination to remove taste and odor compounds; filtering through an activated carbon filter before chlorination would likely improve water quality by reducing DBP precursor concentrations, but the capacity of the activated carbon filter for DOC adsorption would need to be evaluated.

UV Studies

In addition to the bench-scale chlorination studies, a full-scale residential rainwater catchment system that used harvested rainwater as its primary potable water supply was sampled. The catchment surface is a Galvalume® metal roof, and the harvested rainwater is stored in two 5000-gal polypropylene cisterns. Rainwater is filtered through two sediment filters with nominal pore sizes of 25 and 5 μm and disinfected with a UV bulb that emits UV light at 254 nm for a minimum dose of 40 mJ/cm^2. Samples of the raw cistern-stored rainwater and the treated rainwater were collected on four occasions from October 2010 through September 2011. During that time, there was a severe drought in Central Texas, and the maximum air temperature exceeded 37.8 °C on 85 days.

TCs were detected in the raw rainwater in every sampling instance and were an order of magnitude higher during the summer than during the winter. The turbidity in the cistern-stored rainwater also was higher during the summer than during the winter. When the TC concentrations and turbidity were low ($<10^3$ CFU/100 mL and <3 NTU), the treatment system sufficiently disinfected the rainwater (TC <1 CFU/100 mL). When they were high ($>10^4$ CFU/100 mL and >10 NTU), however, the rainwater was not adequately disinfected; TCs on the order of 10^2-10^3 CFU/100 mL were detected in the treated water in July and September 2011. These results suggest that filtration followed by UV irradiation can be an effective treatment system for potable harvested rainwater, but its efficacy can be compromised by high turbidity in the cistern.

To examine individual impact of the filters and UV lamp on treated water quality, as well as the effect of their age on treated water quality, samples were collected at multiple points within the treatment system on one occasion when the system owner replaced each component as part of routine maintenance. As expected, the filters reduced the turbidity and TC concentration, and the UV bulb reduced the TC concentration. Changing the filters and UV bulb did not affect the water quality.

Conclusion

In summary, harvested rainwater can be used as a domestic potable water supply if it is treated properly. Chlorination followed by activated carbon filtration appeared adequate (TC <1 CFU/100 mL and TTHM <80 μg/L) for treating rainwater harvested from the metal and concrete roofs when a chlorine residual of 2 mg/L after 10 min was targeted. This target achieved adequate disinfection in rainwater harvested from the shingle roof but, depending on the DOC concentration, had the potential to form THMs that exceeded the USEPA MCL of 80 μg/L. Chlorine did not appear to be a suitable disinfectant for rainwater harvested from the green roof, likely because of its high DOC concentration. Filtration followed by UV irradiation adequately disinfected cistern-stored rainwater when the turbidity and TC concentration in the influent were low, but treatment was compromised as these two parameters increased as the temperature increased and the drought progressed.

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An Assessment of Water Availability in Texas Using the NOAH Land Surface Model

Basic Information

Title:	An Assessment of Water Availability in Texas Using the NOAH Land Surface Model
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Focus Category:	Climatological Processes, Drought, Hydrology
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Principal Investigators:	C. Prakash Khedun, Vijay P Singh

Publications

1. Khedun, C. P., A. K. Mishra, J. D. Bolten, H. K. Beaudoing, R. A. Kaiser, J. R. Giardino, and V. P. Singh, 2012, Understanding changes in water availability in the Rio Grande/Río Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model, J. Geophys. Res., 117(D5), D05104.
2. Khedun, C. P., H. Chowdhary, A. K. Mishra, J. R. Giardino, and V. P. Singh, 2012, Water Deficit Duration and Severity Analysis Based on Runoff Derived from the Noah Land Surface Model, Journal of Hydrologic Engineering (under review).
3. Khedun, C. P., H. Chowdhary, A. K. Mishra, J. R. Giardino, and V. P. Singh, 2011, Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, “in” 2011 Symposium on Data-Driven Approaches to Droughts, Purdue e-Pubs, Purdue University, West Lafayette, IN.
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An Assessment of Water Availability in Texas Using The Noah Land Surface Model

USGS Grant 2011TX395B

Final Report

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TITLE: AN ASSESSMENT OF WATER AVAILABILITY IN TEXAS USING THE NOAH LAND SURFACE MODEL

PROJECT NUMBER: 2011TX395B

PRIMARY PI: C PRAKASH KHEDUN

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ABSTRACT

The state of Texas suffers from both short term and long term droughts, which have resulted in losses equivalent to several billions of dollars. The recent exceptional drought that hit the southern United States is the worst drought on record for the state of Texas; associated loss to the state's agricultural sector is estimated at $5.2 billion, making it the costliest drought on record. Several studies have shown that precipitation and indeed drought are strongly related to climate teleconnection patterns. Spatial correlation between climate and drought indices shows that watersheds across the state are not uniformly affected by droughts – instead some are more vulnerable than others. While this qualitative information is useful to the water manager, it does not help the latter to plan adequately. In this study we used the Noah land surface model to model water availability in the Rio Grande basin – a transboundary basin shared between three states in the US and straddles the state of Texas and Mexico. It was found that El Niños (La Niñas) generally cause an increase (decrease) in runoff, but the pattern is not consistent; percentage change in water availability varies across events. Further, positive Pacific Decadal Oscillation (PDO) enhances the effect of El Niño and dampens that of La Niña, but during neutral/transitioning PDO, La Niña dominates meteorological conditions. Long El Niños have more influence on water availability than short duration high intensity events. We also note that the percentage increase in water availability during El Niños significantly offsets the drought-causing effect of La Niñas. The results from this study will help give an early warning on expected changes in water availability to water managers and thus help in the medium and long term water planning.

PROBLEM AND RESEARCH OBJECTIVES

Large scale circulation indices such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have a significant influence on local atmospheric and hydrologic variables and hence water availability. Several studies have investigated the influence of climate teleconnections on precipitation [e.g. *McCabe and Dettinger*, 1999; *Piechota and Dracup*, 1996; *Ropelewski and Halpert*, 1986; *Woolhiser et al.*, 1993], streamflow [e.g. *Barlow et al.*, 1998; *Kahya and Dracup*, 1993; *Redmond and Koch*, 1991], and drought [e.g. *Özger et al.*, 2009; *Schoennagel et al.*, 2005]. The information provided by studies conducted thus far is not completely useful for water planners and managers as they provide qualitative information on the degree of association of these hydrologic variables and climate patterns.

In this study we investigate the influence of two large-scale climate indices, namely ENSO and PDO, on the water availability in one of the most important basins in the United States and the state of Texas – the Rio Grande/Río Bravo del Norte basin (RG). RG is a transboundary basin shared between three states in the US and straddles US and Mexico, two countries very dissimilar economically. It is a vital source of water for the region, but is already in a state of absolute water scarcity, with less than 500 m^3/person/day; the only transboundary basin in this category [*Wolf*, 2002]. This region is also extremely vulnerable to droughts; records show that it suffers from both short-term and long-term droughts [*Quiring and Goodrich*, 2008]. Subjected to a burgeoning population, which will further increase the stress on water allocation, and climate change, which will likely result in a decrease in precipitation [*IPCC*, 2007], the potential for conflicts cannot be overlooked. It is therefore imperative to understand the mechanisms driving water availability and quantify any change for long-term sustainable water planning and management.

MATERIALS/METHODOLOGY

The Noah land surface model (LSM) was used to develop a hydrologic model of the basin. The model was developed within NASA GSFC's Land Information System [LIS; *Kumar et al.*, 2008; *Peters-Lidard et al.*, 2007] and driven with the North American Land Data Assimilation System Phase 2 dataset [NLDAS-2; *Mitchell*, 2005].

Noah Land Surface Model

Noah LSM is a stand-alone 1-D column model that can simulate soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack depth, snowpack water equivalent, canopy water content, and water and energy flux terms of the surface water and energy balance [*Mitchell*, 2005]. It has a 2 m deep soil layer divided into the following four sub-layers: a 100 mm thick top layer, a second 300 mm thick root zone layer, a 600 mm deep root zone layer, and a 1000 mm thick sub-root zone layer. The latter layer acts as a reservoir with gravity drainage at the bottom. The volumetric soil moisture content obeys the law of conservation of mass and is determined using the diffusive form of Richard's equation which is derived from Darcy's law under the assumption of rigid, isotropic, homogeneous, and one-dimensional vertical flow. The total evaporation, in the absence of snow, is the sum of direct evaporation from the topmost soil layer, evaporation of precipitation intercepted by plant canopy, and transpiration from canopy of vegetation. The model adopts a gravity free-drainage subsurface scheme, and surface runoff is the excess after infiltration [*Schaake et al.*, 1996]. *Chen and Dudhia* [2001] give a complete description of the model physics and order in which computations are carried. Noah has been a candidate in major off-line land surface experiments, such as the Project for Intercomparison of Land-surface Parameterization Schemes [PIPLS; *Henderson-Sellers et al.*, 1996] and the Global Soil Wetness Project [GSWP; *Dirmeyer et al.*, 1999], among others. It has been validated in both coupled and uncoupled modes [*Mitchell*, 2005] and is implemented in the MM5 modeling system (http://www.mmm.ucar.edu/mm5/mm5-home.html), the Weather Research and Forecast (WRF; http://www.wrf-model.org) model and also NCEP's operational Global Forecast System (GFS; http://www.emc.ncep.noaa.gov/GFS/).

Noah has been extensively tested against other LSMs and has been found to have a small bias in both evaporation and runoff when compared with observed annual water budget and is able to reproduce streamflow with high accuracy [*Mitchell et al.*, 2004], thus making it a suitable candidate for modeling runoff in RG.

North American Land Data Assimilation System – Phase 2

NLDAS-2 was used as forcing data for the model. It has a 1/8° latitude/longitude resolution over a domain covering the conterminous United States, part of Canada, and Mexico (125°W–67°W, 25°N–53°N), thus allowing the modeling of both the US and Mexican portions of the basin. The dataset has been extensively compared, tested, and validated for snow cover and snow water equivalent [*Pan and Mahrt*, 1987; *Sheffield et al.*, 2003], soil moisture [*Schaake et al.*, 1996], and streamflow and water balance [*Lohmann et al.*, 2004]. Additional parameters required as inputs to Noah include land cover [*Hansen et al.*, 2000], seasonal maximum snow free albedo maps, monthly greenness fraction, bottom temperature, and soil texture (sand, clay, and silt) and color [*Zobler*, 1986].

Model Output

The LSM is run retrospectively for a period of 30 years (1 January 1979 to 31 December 2008) at a time step of 30 minutes and output files are written for every 3 hours, thereby creating 8 files for each day from which runoff was extracted at the pixel scale and spatially averaged and temporally aggregated over the region of interest. Both the precipitation and the modeled runoff were validated. The precipitation field was compared to gauged measurements and the monthly runoff was validated against flow in the Río Conchos sub-basin and it was found that Noah faithfully captured the monthly variation in runoff in the basin. A comprehensive description of the modeling and validation exercise is available in *Khedun et al.* [2012b].

Using the modeled runoff and standardized runoff index as a proxy for water availability, water deficit durations and associated severity of drought events were extracted and copula was employed to analyze the bivariate characteristics of water deficit duration and severity in different parts of the basin [*Khedun et al.*, 2011; 2012a].

PRINCIPAL FINDINGS

The principal findings of the study are given below. The first section highlights the main conclusions from the study on the influence of ENSO and PDO on water availability and the second section summarizes the results from a bivariate water deficit duration and analysis based on the Noah model runoff.

Influence of ENSO and PDO

It was found that ENSO and PDO do indeed influence local meteorological and hydrological variables, and hence water availability in RG. The correlation between PDO and three ENSO indices, namely Niño 3.4, MEI, and EMI, with gauged precipitation respectively showed that both ENSO and PDO have a strong influence on the winter and spring precipitation in the basin. The overall correlation is positive, except for the Upper RG region which includes the headwaters in the San Juan range in the Rocky Mountains in southern Colorado. Therefore, higher snowfall during La Niña conditions may help in maintaining flow in the river and offset precipitation reduction in arid/semi-arid New Mexico.

A general increase (decrease) in water availability during El Niños (La Niñas) was noted but some individual events actually caused a decrease (increase) in water availability. By classifying El Niño and La Niña events using criteria such as duration or maximum (or minimum sea surface temperature anomaly), it was found that not all ENSO events are created equal. Some have short duration but high intensities while others may linger for several years. By further investigating the effect of the different ENSO events thus classified on water availability, it was found that El Niños lingering for long periods have more influence on water availability than short duration high intensity events. The upper-middle section of the basin records a higher increase in winter water availability during El Niño events (200-300%) while the lower half, including the Río Conchos, experiences a more modest change. A positive PDO enhances the effect of El Niño and dampens the negative effect of La Niña. When it is in its neutral/transition phase, La Niña dominates climatic conditions and reduces water availability. Finally, the percentage increase during El Niños significantly offset the decrease registered during La Niñas. This finding is important for water resources planning.

Bivariate Water Deficit and Severity Analysis

In order to assess the bivariate water deficit and severity, the basin was divided into 6 sub-regions, since the basin is subject to different climatological conditions, and nine copulas are tested on each region using graphical assessment and analytical goodness-of-fit tests. It is found that given that water deficit duration and severity characteristics varied across regions, different copulas are deemed suitable.

The conditional probability models for severity given a threshold duration and duration given a threshold severity were found to be different. Comparing two climatologically distinct regions (Upper RG and Lower-Middle RG) it was found that the conditional probability of minor events are almost similar but that for long duration high severity events are very different, reflecting the nature of deficit events in these regions.

Finally it was found that model derived water deficit conditional probabilities can be used in tandem with observation driven conditional probabilities for long term water planning and management and model derived information may be used in regions having limited ground observation data.

SIGNIFICANCE

This study extends the discussion between the influence of large-scale circulation indices and local meteorological and hydrological conditions by quantifying the seasonal percentage changes in water availability, which is more tangible information for water planning. Climate change may alter the frequency and intensity of ENSO events and may cause droughts that are more extreme and/or of longer duration than on record. The current results, while are not intended for prediction purposes, may help in the long-term sustainable water planning and management within the basin for Texas, the United States, and Mexico. Finally, the methodology developed in this study is not limited to RG, but can be adapted to other watersheds in Texas and can even be applied to larger continental scale to assess the need and effectiveness of interstate water transfers for example.

PUBLICATIONS

The funds from the USGS Grant 2011TX395B along with other funds were used to support the following two peer-reviewed publications (one is currently under review), a poster and a paper at the 2011 Symposium on Data-Driven Approaches to Droughts, and a poster at the 2011 American Geophysical Union Fall Meeting.

Peer-reviewed Publications

Khedun, C. P., A. K. Mishra, J. D. Bolten, H. K. Beaudoing, R. A. Kaiser, **J. R. Giardino**, and **V. P. Singh** (2012), Understanding changes in water availability in the Rio Grande/Río Bravo del Norte basin under the influence of large-scale circulation indices using the Noah land surface model, *J. Geophys. Res.*, *117*(D5), D05104.

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2012), Water Deficit Duration and Severity Analysis Based on Runoff Derived from the Noah Land Surface Model, *Journal of Hydrologic Engineering (under review)*.

Conference Paper

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, in *2011 Symposium on Data-Driven Approaches to Droughts*, Purdue e-Pubs, Purdue University, West Lafayette, IN

Conference Poster

Khedun, C. P., H. Chowdhary, A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Analysis of Drought Severity and Duration Based on Runoff Derived from the Noah Land Surface Model, in *2011 Symposium on Data-Driven Approaches to Droughts*, Purdue e-Pubs, Purdue University, West Lafayette, IN

Khedun, C. P., A. K. Mishra, **J. R. Giardino**, and **V. P. Singh** (2011), Probabilistic Water Availability Prediction in the Rio Grande Basin using Large-scale Circulation Indices as Precursor, *American Geophysical Union*, Fall Meeting 2011, Abstract #H43H-1333

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Benefits and Costs of Water Reuse Programs in Texas

Basic Information

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Principal Investigators:	Shae Luther, Laura J Stroup

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REPORT

Title: Benefits and Costs of Water Reuse Programs in Texas

Project Number: 8000001618

Primary PI: Shae R. Luther

Other PIs: Dr. Richard W. Dixon

Abstract

As Texas's population is expected to reach approximately 46 million by 2060, water managers will need to find more sustainable water supplies to accommodate this increase. Overallocation of many of the state's rivers, as well as overpumping of aquifers, makes these resources less reliable for meeting growing water demands. For this reason, many decision-makers are turning toward creative water reuse initiatives to augment dwindling supplies, as water use for municipal purposes has already increased exponentially over the last several years. This research focuses on Potter, Midland, Lubbock, and Collin counties since each report more than ten million gallons per day of municipal water supply reuse, according to the Texas Water Development Board. The first portion of this study examines similarities and differences between these counties to determine how each community incorporates reuse into their municipal water supply. Additionally, for a reuse project to be effective and successful, the local community must be onboard, and therefore should be included in the planning and implementation process. The second portion reports on the results of a survey of residents of these counties. We analyze and assess their perceptions regarding reuse to evaluate the extent to which they are willing to accept various reuse initiatives.

Problem and Research Objectives

Diminishing water supplies are of growing concern in many Texas communities. Water managers struggle to find sustainable water resources to meet growing municipal demands. One consideration is implementing more aggressive water reuse initiatives, but in order to plan and employ successful reuse programs, it is imperative to first document and consider the social and environmental benefits and costs of water reuse.

Water agencies have used reclaimed and reuse water for many years as non-potable water resources. Water reuse saves clean, potable water resources by providing additional supplies for irrigation, industrial, and other uses (Hartley 2005). However, water reuse can also serve a critical role in meeting growing potable water demands (TWDB 2007). In many regions of the United States, a common practice includes releasing wastewater effluent into waterways to be reused directly downstream (Stephens 2005). Indirect reuse such as this is an accepted water supply resource. If not managed and promoted effectively, however, public reaction to more direct uses of reuse water can hinder projects and create increasing challenges for water managers (Po et al. 2003; Stephens 2005).

Texas lacks firm, available water supplies to meet currently experienced population growth rates. Additionally, large portions of the state are drought-prone, which further depletes existing supplies. To be able to meet growing demands, water managers need to incorporate a number of strategies to achieve sustainable water resources, including water reuse. Texas contains a diversity of climatic regions and varied community perspectives, which will therefore require different strategies and priorities for water management.

Having a better understanding of each region's water priorities, and the community's perceptions regarding potable reuse water supply, will provide information for water managers and stakeholders to more effectively plan and utilize various types of water reuse initiatives. Further, including the public in the planning process will increase the likelihood of acceptance of the chosen reuse programs. Inclusionary practices, incorporating community feedback in terms of both their perceptions and ideas, will provide frameworks for strong, community-backed wastewater reuse plans, within relevant local contexts.

The counties studied include Potter, Lubbock, Midland, and Collin. Potter is located in the Texas Panhandle, Midland and Lubbock are in West Texas, and Collin is located in North Central Texas. Each county reports more than ten million gallons of water per day of municipal water reuse, more than the other counties in the state, making them ideal candidates for a research project focusing on water reuse in Texas (Alan Plummer Associates 2010, 2010a).

Materials/Methodology

This project focused on two objectives.

<u>Objective 1:</u> Examined the similarities and differences between these counties, as well as the regions in which they reside, as well as how each incorporates reuse into their municipal water supply. Interviews with water managers and planners provided insight into the decision-making processes: what types of reuse initiatives are being utilized, benefits and costs of each reuse program, and how or if the community was involved throughout the process. The researcher completed in-person interviews with water managers in all counties, except Lubbock, where the interview was over-the-phone. For Potter, Lubbock, and Midland, only one interview was needed as there was only one municipal water supplier in each of these counties, as people living outside the scope of city municipalities were on well water. Collin County is more heavily urbanized than the other three, but since all municipalities in the county rely on North Texas Municipal Water District for their water supply, two interviews were completed for Collin. Finally, effluent and reuse amounts were also analyzed to compare supply and demand for each county.

<u>Objective 2:</u> Surveyed a sample of residents from each county to assess their perceptions concerning water reuse, what factor(s) convinced them to accept reuse plans (if at all), and to what extent they would be willing to utilize direct-to-reuse water sources. The researcher utilized an online questionnaire that consisted of both Likert Scale and open-ended questions. Postal delivery routes were randomly chosen and an initial postcard and follow-up postcard were mailed to potential participants, pointing them to the on-line survey.

Principal Findings

Water reuse is not new to West Texas or the Panhandle. Agricultural irrigation with reclaimed wastewater dates back to the late 1880s, petrochemical companies and oil refineries began direct reuse of water in the 1940s, and in the 1960s, water reclamation increased with municipality reuse programs. In counties such as Midland and Lubbock, water sources, regardless of origin, was vital to the community. Today, Midland and Lubbock counties recycle all treated effluent without returning any to a streambed for downstream use, as most, if not all, of the streams in these areas are intermittent at best. In the more humid north Texas region, Collin County does have return flows, with a total of 70% being recaptured and 30% being legally mandated for downstream uses. All interviewed water managers see reuse water as a benefit in conserving potable water supplies since it is a continuous source that can be utilized for water-intensive needs, such as irrigation. Similarly, 97% of survey participants agree water reuse is a valid conservation strategy for preserving fresh, potable water sources. All current reuse projects relating to potable supplies are indirect through augmentation of freshwater resources. Considering the increase in drought severity and limited resources, all water managers consider the potential for direct potable reuse to be a viable option in the future. Survey answers show the biggest concerns for community members lie in water demands/population growth, continued/future droughts, and lack of conservation, but only 8% of participants stated they would accept or potentially accept direct potable reuse.

According to the water managers, public participation in the planning process for current or planned reuse projects was minimal since the type of projects being implemented did not directly impact the general public as a whole. Meetings and/or educational workshops that were offered focused on conservation rather than reuse, and most of these were town hall meetings or presentations to civic groups. A few of the managers claimed to use the term "raw" water supply in place of "reuse," "reclamation," and "recycled" water in an effort to minimize negative reactions. Survey participants, however, expressed concern over these types of meetings, stating there was no open discussion, but rather a forced agenda; data presented was untruthful; or meetings were poorly set up and not interesting to sit through. Even still, 78% claimed they would attend meetings specifically discussing water reuse as a water supply strategy for their region.

As already stated, 97% of respondents agree reusing treated wastewater is beneficial for conserving freshwater resources. Perceptions on acceptable uses differ, however. Seventy-three percent stated irrigation is a good way to utilize reclaimed water. For purposes of this research, irrigation includes agricultural, personal and municipal landscaping, and watering of houseplants. Three of the fifty-five that answered this particular question claimed to be comfortable with reusing water, but did not want it used for any purpose that could contact the skin, such as bathing or swimming. Two of those three did not even want it used on residential lawns or for irrigating public parks. Their concerns lie in feeling unsure of the health risks of water reuse. More importantly, though, 8% responding to this same question either are, or would be, agreeable to more direct potable reuse if shown the water was treated to high enough standards for safety.

The topics mentioned most in answers to the open-ended questions focused on conservation and future supplies. Thirty-four percent commented on the wastefulness of water resources in their communities, either through overwatering of lawns, continued watering of football fields and golf courses, or a basic lack of conservation effort. Others were apprehensive over continued droughts and increased water demands due to population growth, 30% and 23% respectively. Two people expressed irritation at the city they lived in because they continued to draw in large businesses without having a firm water supply for future needs that could accommodate the growth new businesses brought into the region. In response to how participants thought water reuse could alleviate some of their concerns, an overwhelming majority (81%) said reuse for non-potable purposes could conserve freshwater resources for potable use and would help ensure future supplies.

Significance

Water reuse strategies are growing as viable options in Texas. As a resource, the amount of treated effluent grows with the population and is always an available supply. In general, communities are familiar with conservation practices and fairly familiar with reuse, but the two are not always presented as part of the same goal, if water recycling is discussed at all. Many people still have an aversion to the idea of reclaiming wastewater, especially if the water comes in contact with food products or the body. If drought severity continues to increase as it has over the last few years, and populations in Texas continue to grow at exponential rates, communities may need to accept the notion of direct potable reuse in the future. In fact, one city outside the counties researched for this study is already facing such a predicament. Therefore, public education programs are imperative to gaining community support for more direct water reuse programs, especially in areas such as Midland and Lubbock where water shortages are more likely. Not only does it open up communication lines, it allows water managers the opportunity to address public concern over health issues related to water reuse. If information is managed and presented correctly, water providers can positively influence community stakeholders' perceptions and promote acceptance of water reuse programs through effective education.

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WATER REUSE SURVEY RESULTS SUMMARY

Presented to TWRI/USGS as part of final grant report, 14 May 2012

There were 75 responses to the survey (1.5% return) of which 11 were eliminated because the respondents did not live in a targeted county.

1. Which county do you live in?

	N	%
Collin:	32	50
Lubbock:	18	28
Midland:	10	16
Potter:	4	6

2a. Water reuse is acceptable only when there is a genuine need, such as during a drought.

		N	%
Strongly Agree	=	7	11
Agree	=	5	8
Strongly Disagree	=	24	37.5
Disagree	=	20	31
Neutral	=	8	12.5

b. Recycling treated wastewater for non-potable uses is a good way to conserve clean water sources for potable supplies.

		N	%
Strongly Agree	=	33	52
Agree	=	29	45
Strongly Disagree	=	1	1.5
Disagree	=	1	1.5
Neutral	=	0	0

c. Treated wastewater should only be used for non-potable purposes.

		N	%
Strongly Agree	=	21	33
Agree	=	23	36
Strongly Disagree	=	2	3
Disagree	=	4	6
Neutral	=	14	22

d. I believe my region has sufficient water supply to meet future needs.

		N	%
Strongly Agree	=	2	3
Agree	=	11	17.5
Strongly Disagree	=	20	32
Disagree	=	19	30
Neutral	=	11	17.5

3. ***What do you see as acceptable uses for reclaimed wastewater? (55 responses)***

Respondents gave multiple answers to this question.

Irrigation (includes agricultural, landscaping, and house plants): 73%
Car washes: 27%
Everything (includes potable or potentially potable): 15%
Anything except drinking and cooking: 11%
Toilets: 13%
Industrial (includes fracking and oil fields): 13%

Other uses mentioned included construction sites, highway projects, cooling towers for power generation, decorative fountains and ponds, fire hydrants, appliances, wildlife habitats, showers, and pet bathing.

Three specifically mentioned they were not okay with skin contact, such as showering, and two of those did not want it used on lawns or public parks.

4. ***Please explain any concerns YOU may have regarding future water supplies in your area. (53 responses)***

Respondents gave multiple answers to this question.

Waste/Lack of conservation: 34%
Droughts/Other shortages: 30%
Population growth: 23%
Sustainability/Lack of firm future supply: 23%

Other concerns mentioned included an increase in rates, zebra mussel infestations, cleanliness of potable supply, restrictions, and infrastructure.

5. ***How could water reuse address the concerns you describe in question 4? (52 responses)***

Respondents gave multiple answers to this question.

Conservation of/Ensure freshwater supplies: 81%

Survey participants also stated water reuse could address their concerns by reducing water rates, alleviating restrictions, and simply being beneficial overall. Three people (6%) did not think it would help.

6a. Water managers should consider public input when planning for future water supplies.

		N	%
Strongly Agree	=	29	45.3
Agree	=	31	48.4
Strongly Disagree	=	0	0
Disagree	=	0	0
Neutral	=	4	6.3

b. Public education programs should be developed and offered so the community can obtain a better opportunity of how reused water can be utilized as part of their total regional water supply.

		N	%
Strongly Agree	=	39	62
Agree	=	19	31
Strongly Disagree	=	1	2
Disagree	=	1	2
Neutral	=	2	3

7. Are you the type person who would attend community meetings?

		N	%
Yes	=	21	33
No	=	13	20
Only if interested in topic	=	30	47

8. Would you attend a meeting discussing water reuse as a water supply strategy?

		N	%
Yes	=	50	78
No	=	14	22

8a. If no, why not?

Of the 14 participants that said "no," only 12 responded to this question.

Time/Busy: 33%

No communication/discussion during meetings or forced agenda: 25%

Boring or not important enough use of time: 17%

Not staying in community/doesn't feel need to input since living in apt: 17%

Untruthful/not factual: 8%

Limited transportation: 8%

9. Age group:

	N	%
18-29:	9	14
30-45:	20	32
46-59:	20	32
60+:	14	22

10. Male or Female?

	N	%
Males:	33	52
Females:	30	48

11. How many people live in your home?

	N	%
1 person:	14	22
2 people:	18	28
3 people:	14	22
4 people:	14	22
5 people:	4	6

12. How long have you lived at this residence?

	N	%
<1 year:	7	11
1-5 years:	30	47
6-10 years:	12	19
11-15 years:	4	6
16-20 years:	3	5
>20 years:	8	12

13. Own/rent? (63 responses)

	N	%
Own:	41	65
Rent:	22	35

14. Is your residence connected to city water or well water?

	N	%
Wells:	2	3
City:	62	97

15. City sewage or septic?

	N	%
Septic:	2	3
City:	62	97

16. What is your highest level of education?

	N	%
Some high school:	1	1.6
High school/GED:	3	4.7
Some college:	14	21.9
Bachelor's:	20	31.3
Master's:	19	29.6
Doctorate:	7	10.9

Effects of woody vegetation removal on groundwater recharge in the Carrizo-Wilcox aquifer

Basic Information

Title:	Effects of woody vegetation removal on groundwater recharge in the Carrizo-Wilcox aquifer
Project Number:	2011TX397B
Start Date:	1/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	23
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Ecology, Management and Planning
Descriptors:	None
Principal Investigators:	April Mattox, Jason West

Publications

There are no publications.

REPORT

Title: **Effects of woody vegetation removal on groundwater recharge in the Carrizo-Wilcox aquifer**

Project Number: 2011TX397B

Primary PI: April Mattox

Other PIs: Jason West

Abstract: The Carrizo-Wilcox aquifer is an important source of water for agricultural and municipal needs across approximately 60 counties in Texas. As use of the aquifer increases and managers look for methods to increase recharge rates, understanding the effects of woody vegetation removal on recharge is becoming more important. However, surprisingly little research has been done to quantify the impacts of such actions on recharge. This project will investigate the impacts of woody vegetation removal from the recharge zone of the Carrizo-Wilcox aquifer on downward fluxes of vadose zone soil moisture in a replicated field experiment. Given the difficulties associated with quantifying recharge in semi-arid systems such as this one, we employ multiple indirect methods across the experiment, validated by an intensive instrumentation effort. The proposed research will provide quantitative information needed by the groundwater conservation districts and landowners throughout the region.

Problem and Research Objectives: Understanding the effects of vegetation on groundwater recharge is important in areas such as the Winter Garden Groundwater Conservation District where vegetation is being managed for various outcomes and by different means. Rangelands across Texas are subject to a variety of management practices and are managed for a variety of reasons. Some land is managed to improve grazing for cattle, while some is managed to improve bird or deer habitat for hunting. Increasingly, managers are explicitly engaged in activities to improve aquifer recharge. In consideration of all of the reasons why vegetation is being removed and to what degree, it is important to understand what the impacts are on groundwater. At this time, there is very little scientific information for the Carrizo-Wilcox region to support decisions about removal of vegetation and its subsequent effects on groundwater. Even less is known about the role of soil type or texture on the effects of vegetation removals.

Our primary objective is to enhance the interpretation of planned indirect estimates of aquifer recharge in a large, manipulative field experiment through targeted direct measurements of moisture flux below the root zone. Our current approach is to estimate recharge indirectly using monthly neutron moisture meter measurements, stable isotopes and continuous moisture measurements across the experiment.

Materials/Methodology:

In this experiment we are removing woody vegetation using three commonly-applied mechanical and chemical techniques, as well as evaluating their interaction with cool-season fires and how these techniques interact with soil texture. The techniques used for removal of woody vegetation span the range of impacts associated with common brush removal techniques from no impact (control plots) to moderate mortality (roller chopping) to near 100% mortality of woody species (chainsaw plus herbicide of all woody stems).

Quantifying recharge in these semi-arid systems is difficult and the application of multiple techniques increases the reliability of recharge estimates (Scanlon et al. 2002). We will be making assessments of water movement from volumetric water content measurements, soil texture,, and stable isotopes (d^2H and $d^{18}O$) throughout the soil profile. To allow an assessment of shorter-term responses, soil moisture stable isotope ratios will be analyzed. The combination of continuous moisture measurements and stable isotope data will provide critically important information about recharge. The additional funding provided by USGS was used to purchase the continuous moisture meters and associated data loggers. The additional instrumentation allowed us to measure volumetric water content of soils on an hourly basis to detect short term changes that would not be been in the monthly measurements using the neutron probe. The matching funds provided by the Wintergarden Groundwater Conservation District were used for graduate student support for April Mattox

Principal Findings: Soil moisture measurements have been taken continuously at 6 sandy locations since mid-January. Continuous measurements have detected changes in soil water content that would have otherwise been missed with monthly neutron moisture meter measurements. The continuous measurements are also corroborating evidence of no change in soil water content at some depths in some locations.

Significance: This additional data improves our confidence in understanding soil water dynamics *in situ* under natural conditions. The findings will help to determine the effects of woody vegetation removal on soil water movement. The additional data obtained thru funding by USGS will allow finer scale measurements of soil water movement that otherwise would not have been possible.

PUBLICATION

There was no publication of data for this project during the reporting period of the grant.

NOTABLE AWARDS AND ACHIEVEMENTS

There have not yet been notable achievements or awards resulting from work supported by section 104 and required matching funds and by supplemental grants during the reporting period.

Evaluation of Grass Carp (Ctenopharyngodon idella) as a Biocontrol Agent for Giant Salvinia (Salvinia molesta)

Basic Information

Title:	Evaluation of Grass Carp (Ctenopharyngodon idella) as a Biocontrol Agent for Giant Salvinia (Salvinia molesta)
Project Number:	2011TX398B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	17, 26
Research Category:	Ecological Processes
Focus Category:	Ecology, Invasive Species, Water Supply
Descriptors:	None
Principal Investigators:	Michael Neisch, Michael Masser

Publications

There are no publications.

REPORT

Title
Evaluation of Grass Carp (Ctenopharyngodon idella) as a Biocontrol Agent for Giant Salvinia (Salvinia molesta)

Project Number
2011TX398B

Primary PI
Michael Neisch

Other PIs
Dr. Michael Masser, Dr. Daniel Roelke

Abstract
Giant salvinia (Salvinia molesta) and hygrophila (Hygrophila polysperma) are both invasive, introduced macrophytes that have quickly become established in Texas waters. First identified in Texas in 1998 near Houston, giant salvinia is now found in Lake Conroe, Toledo Bend Reservoir, Caddo Lake, and at least eight other public Texas impoundments. Listed as one of the most problematic aquatic plants by the state, giant salvinia is a floating fern capable of doubling its spatial occupation in a week. It can displace native aquatic plants that provide food and habitat for invertebrates and fish and produces a floating mat that blocks sunlight and reduces dissolved oxygen concentrations to dangerously low levels. Hygrophila is a fast growing and spreading submerged macrophyte capable of occupying the entire water column and outcompeting native species. It was first documented in the San Marcos River in the 1960's, and has spread to many drainages and impoundments throughout the state, including Caddo Lake. This research evaluated the potential use of triploid grass carp (Ctenopharyngodon idella) as a biological control agent for these two novel invasive species. Using a controlled mesocosm experiment, maximum consumption rates and feeding preferences were measured. Giant salvinia and hygrophila were compared to six native and introduced species common in Texas and the Southern US.

Problem and Research Objectives
Determine the maximum consumption rates and feeding preferences of triploid grass carp for two novel invasive aquatic species.

Materials/Methodology
A total of 8 native and invasive aquatic plants were collected from Texas waterways and introduced to triploid grass carp. Using a controlled mesocosm experiment, maximum consumption rates and feeding preferences were established through a series of paired comparison trials.

Principal Findings

Research has been completed and is currently being analyzed. Data will be presented at the 52nd Annual Meeting of the Aquatic Plant Management Society, and will also be published in the Masters thesis of Michael Neisch.

Significance

Triploid grass carp can be a potential biological control agent for giant salvinia and other invasive aquatic plants that are a significant threat to Texas' water resources. The use of triploid grass carp in controlling invasive plants can reduce the dependence on herbicides and provide a longer lasting treatment period.

In Situ Remediation of the Trinity River Sediment Contaminated with Polychlorinated Biphenyls

Basic Information

Title:	In Situ Remediation of the Trinity River Sediment Contaminated with Polychlorinated Biphenyls
Project Number:	2011TX400B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	TX-006
Research Category:	Water Quality
Focus Category:	Toxic Substances, Sediments, Treatment
Descriptors:	None
Principal Investigators:	Prince Nfodzo, Hyeok Choi

Publications

There are no publications.

REPORT

Title
In Situ Remediation of the Trinity River Sediment Contaminated with Polychlorinated Biphenyls

Project Number
2011TX400B

Primary PI
Prince Nfodzo, Ph.D. Candidate; Civil Engineering, UT-Arlington

Other PIs
Hyeok Choi, PhD, Assistant Professor, Civil Engineering, UT-Arlington

Abstract
Aquatic sediments are often the ultimate receptors of all kinds of contaminants, in particular highly toxic and persistent polychlorinated biphenyls (PCBs). The sediments act as long term sources for the slow release of PCBs to aquatic environment. Developing effective technologies for cleaning up PCBs-contaminated sites has been one of the highest priorities of USGS, EPA, and DOD. State-level concern was also issued that fish in the Trinity River located in North Texas is not safe for people to eat due to the high level of PCBs. Recently, EPA researcher and Dr. Choi have developed an innovative material, reactive activated carbon (RAC), which possesses capability to physically sequestrate and chemically degrade PCBs, and they have preliminarily tested RAC strategy for the adsorption and dechlorination of PCBs exclusively in pure water. In this present study, we explored the capability of the RAC to treat PCBs in an actual sediment matrix, i.e., PCB-contaminated sediment from the Trinity River in North Texas in order to propose the RAC cap/barrier concept as a new environmental risk management option for PCBs-contaminated aquatic sediments in US.

Problem and Research Objectives
According to US EPA, 10% of the sediment underlying the country's surface water is contaminated with toxic pollutants that pose potential risks to fish, wildlife, and humans [1]. In particular, 200,000 tons of probable human carcinogenic and persistent PCBs were released and deposited to aquatic sediments [2]. The sediments act as long term sources for the slow release of PCBs to aquatic environment. Based on a state study by the Texas Commission on Environmental Quality (TCEQ), the Dallas Morning News reported on February 4, 2010 that fish in the Trinity River located in North Texas will not be safe for people to eat until the levels of PCBs in the river come down by more than half [3]. The article also emphasized that just making a decontamination plan for the Trinity river's PCBs will take two years, and in the end the only answer may be to wait for nature to break down the PCBs which can take decades (due to their recalcitrant and hydrophobic nature). It is also reported that General Electric Co. discharged PCBs into Hudson River, NY for three decades, and the company is now spending over 750 million dollars to remediate the contaminated sites [4]. Unfortunately, the remediation strategy being used is to dredge the sediment and transport it to a PCBs-approved landfill in Andrews, TX. The principal mechanism of this strategy is just physical relocation of the contaminated site to elsewhere. What if cleaning up the PCBs could be done in situ without dredging?

EPA and others have traditionally installed an adsorptive activated carbon layer to simply cap a contaminated site and thus to sequester PCBs in situ [5–7]. However, PCBs are still in the site after remediation. To develop a more aggressive strategy, EPA researcher and Dr. Choi recently synthesized an innovative material, named RAC, as shown in Figure 1 [8]. The pores of adsorptive activated carbon are impregnated with reactive Fe/Pd nanoparticles which posses capability to chemically destroy PCBs. As a new environmental risk management option, they proposed the concept of a RAC cap/barrier that sequesters as well as breaks down PCBs in place [9]. After the pioneering work, many other researchers also started adopting the RAC strategy [10, 11]. For the studies, however, they have used pure aquatic PCBs (i.e., mixture of PCBs and water) to preliminarily elucidate the physical and chemical mechanisms, without considering the complexities of treating PCBs in actual sediment with heterogeneous nature [8–14]. There has been no research study demonstrating that the RAC strategy works for actual sediments contaminated with PCBs. In fact, PCBs tend to strongly attach to the solid surfaces in sediment matrix and thus they are less mobile in the aquatic environment [15, 16]. It is easily expected that the PCBs strongly bound to sediment solids (in particular organic carbon components) are not available for the reaction on RAC. This invokes a critical issue on the implementation of the RAC strategy. Consequently, there is a fundamental and applied research need to answer the following questions: i) does RAC system really work for the remediation of actual sediments contaminated with PCBs? and ii) if so, what are the sequence and nature of the reactions during the remediation?

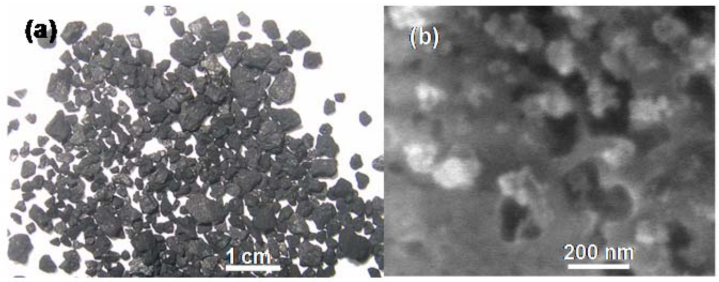

Figure 1. (a) granular RAC typically in size of 2–3 mm and (b) its microscopic cross-section, suggesting that many pores are occupied with Fe/Pd nanoparticles.

Materials/Methodology

Synthesis of Reactive Activated Carbon

The detailed synthesis procedure and route of RAC containing around 14.4% Fe and 0.7% Pd (weight base) was reported previously [8]. Briefly, iron was incorporated into mesoporous GAC (HD 3000, Norit Americas Inc.) in 2-3 mm size *via* an incipient wetness impregnation method. $Fe(NO_3)_3 \cdot 9H_2O$ of 22.8 g was melted at 55–60 ºC, mixed with 10 g of GAC, and then dried at 60–70 ºC using an infrared ramp for 2 h. The GAC/$Fe(NO_3)_3$ composite was further calcined in a furnace at 300 ºC for 4 h to transform $Fe(NO_3)_3$ to Fe_2O_3 and sieved using a #20 to remove unincorporated Fe_2O_3 particles. In order to reduce Fe_2O_3 to zerovalent Fe (ZVI, Fe^0), 1.6 g $NaBH_4$ dissolved in 20 mL water was added to 4 g GAC/Fe_2O_3 suspension in 50 mL of methanol/water (30/70 v/v) at pH 6.5. Then GAC/ZVI was recovered and washed with methanol to remove free ZVI and other impurities, and then dried at room temperature. For Pd doping, the GAC/ZVI was mixed with 75 mg of palladium acetate ($Pd(CH_3CO_2)_2$) dissolved in 20 mL methanol. Then GAC/ZVI/Pd, denoted as RAC composite, was recovered, washed, and dried again. Samples at the end of each procedure were sieved with a #20 sieve to remove grains smaller than 0.85 mm.

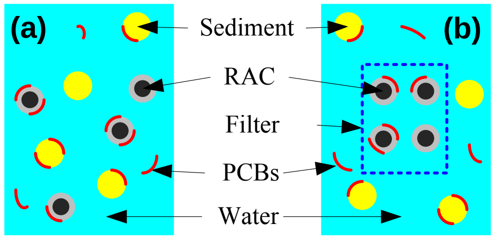

Figure 2. Experimental set up for the treatment of aquatic sediment in configuration of: (a) direct mixing of sediment with RAC and (b) compartment of sediment separated from RAC. PCBs in sediment are partitioned to the water, RAC, and sediment phases. In case of the direct mixing, overall PCBs in the solid mixture of RAC and sediment are measured while in the compartment configuration, PCBs transported to the RAC sector are differentiated from those remaining in the sediment. The compartment configuration conceptually mimics the cap/barrier strategy.

Trinity River Sediment (TRS)

PCB-contaminated sediment was obtained from the West Fork Trinity River at Beach Street, Fort Worth, TX (Station ID 10938). The sample (Trinity River Sediment. TRS) was dried at 105 °C in an oven for 1 d, and ground into fine powder. A set of batch reactors were built with 1 g of RAC, where TRS was directly mixed with RAC in 10 mL water at a RAC:sediment ratio of 1:3 (by weight) to implement the direct mixing configuration shown in Fig. 2(a). To facilitate desorption of PCBs from TRS, 10% acetone or 1% Triton X-100 surfactant was also used. PCBs are possibly partitioned to the liquid, solid WHS, and solid RAC phases. However, this direct mixing configuration makes it difficult to separate RAC from WHS.

Waukegan Harbor Sediment (WHS)

Since we found the level of PCBs in TRS was very low, another sediment heavily contaminated with PCBs was tested in a similar way. Sediment in Waukegan Harbor (Waukegan, IL), one of Superfund sites, was taken and denoted as Waukegan Harbor Sediment (WHS). In a vial, 1.8 g of WHS was mixed with 22 mL of water. A set of batch reactors were built with RAC, where 0.6 g of RAC was directly mixed with WHS. To facilitate desorption of PCBs, 1% of acetone or 1% Triton X-100 surfactant was also used. The direct mixing was further modified to investigate RAC loading effect. The ratio of RAC/WHS at 1:3 was incremented to 1:1, 2:1, and 4:1.

Analysis of PCBs and Reaction Intermediates

The batch reactors were tumbled at 90 rpm in a rotary shaker for up to 100 d. One reactor was sacrificed in each sampling event for extraction and measurement of PCBs in the liquid, WHS, and RAC phases. A detailed description for the extraction (hexane extraction for liquid and automated Soxhlet for solid, EPA Method 3541) and measurement (HP 6890 gas chromatograph/ HP 5973 mass spectrometer, EPA Method 8082) of PCBs was reported elsewhere [8, 9]. The detection limit of each PCB congener was at around 2 µg/L.

Principal Findings

PCB Congeners Distribution in TRS

The concentration of PCBs in TRS is shown in Fig. 3(a). TRS was mildly contaminated with PCBs at 113.6 µg/kg. Tetrachlorinated and trichlorinated biphenyls were dominant. The degree of chlorination of PCBs is 3.3. Meanwhile, after mixing TRS with pure water, PCBs desorbed to water were monitored, as shown in Fig. 3(b). No significant amounts of PCBs were desorbed (even 2 µg/kg of trichlorinated biphenyls is close to the detection limit of GC/MS used), implying that PCBs were strongly bound to TRS solid matrix, as expected.

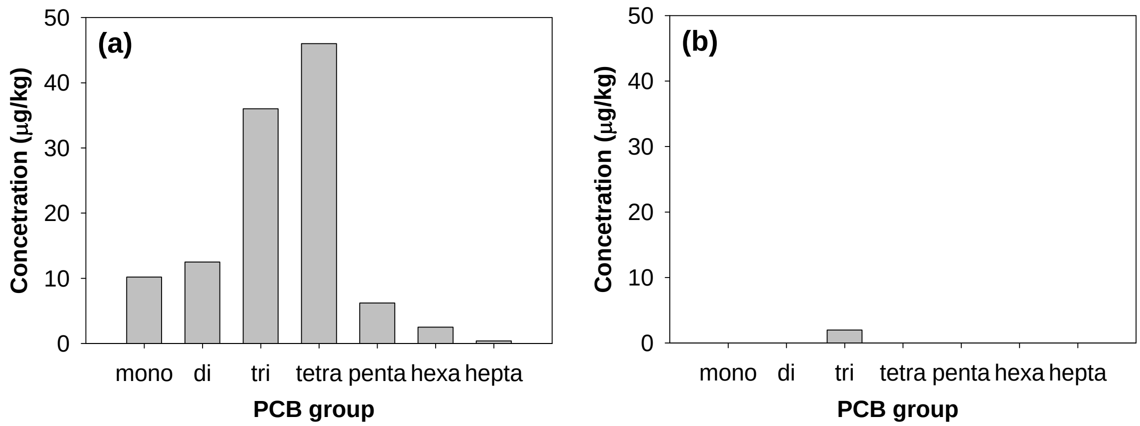

Figure 3. PCB congener distribution in (a) solid matrix and (b) supernatant of Trinity River Sediment (TRS).

Adsorption and Dechlorination of PCBs in TRS

Results on mixing of TRS with RAC are summarized in Fig. 4. Partitioning of PCBs to the liquid phase was negligible (Fig. 4(a)). The result suggests addition of RAC was effective to completely sequester PCBs available in the liquid phase. As shown in Fig. 4(b), changes in the relative PCBs fraction in the solid phase were the most significantly noticeable under 1% Triton X-100 condition. The fraction of higher chlorinated congeners decreased while that of lower chlorinated congeners somewhat increased. Trichlorinated biphenyls accumulated while tetrachlorinated biphenyls exhausted. Biphenyls (no chlorines) were detected. Overall chlorine removal efficiency is presented in Fig. 4(c). The efficiency increased in order of 1% Triton X-100 > 10% acetone > water. Even in cases of water and acetone showing no apparent PCBs partitioning to the liquid phase, desorption of PCBs to the liquid phase is believed to occur, and thus the instantaneously desorbed PCBs are immediately re-adsorbed to RAC and dechlorinated.

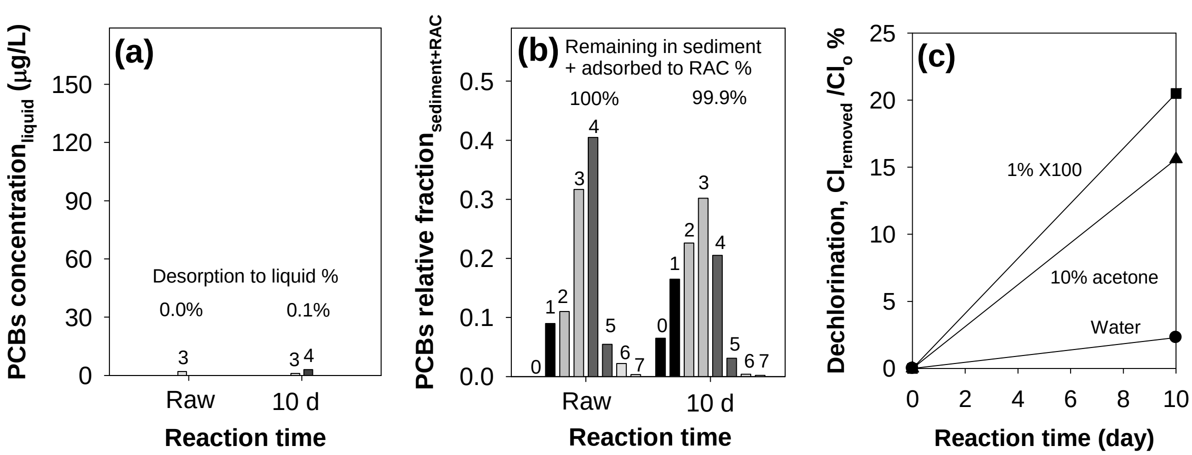

Figure 4. Desorption and adsorption/dechlorination of PCBs in TRS mixed with RAC: (a) PCBs desorbed to 1% Triton X-100, (b) relative fraction of PCBs remaining in the mixture of WHS and RAC after desorption to 1% Triton X-100, and (c) overall dechlorination efficiency based on chlorine removal under various solvent conditions.

PCB Congeners Distribution in WHS

Since the total concentration of PCBs in TRS was too low at 113.6 μg/kg, we had a difficulty to accurately quantify the dechlorination efficiency and thus we decided to test more practical sediment samples containing much higher level of PCBs. The concentration of PCBs in WHS is shown in Fig. 5. WHS was heavily contaminated with PCBs at 35.6 mg/kg. Trichlorinated and tetrachlorinated biphenyls were dominant. The degree of chlorination of PCBs is 3.6. Meanwhile, after mixing WHS with pure water, no PCBs were desorbed to water, implying that PCBs were strongly bound to WHS matrix.

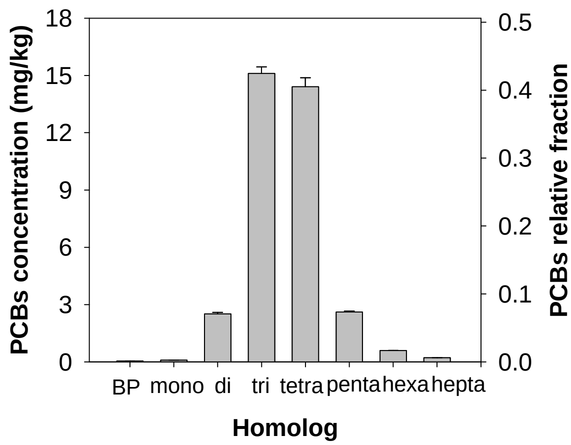

Figure 5. PCB congener distribution in Waukegan Harbor Sediment (WHS). No PCBs were found in the liquid phase.

Adsorption and Dechlorination of PCBs in WHS

PCBs were negligibly detected in water and even in 1% acetone and 1% Triton X-100 surfactant after 100 d mixing. However, certain amount of PCBs might have been desorbed from WHS to the aqueous phase, but immediately partitioned to RAC and dechlorinated. The dechlorination of PCBs in WHS mixed with RAC at various RAC/WHS ratios is shown in Fig. 6.

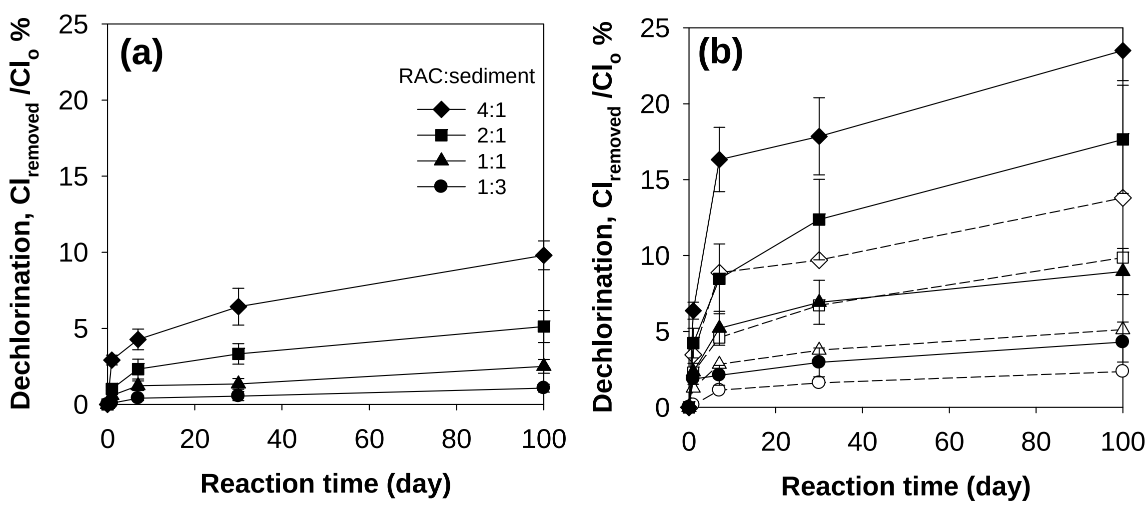

Figure 6. Overall dechlorination of PCBs in WHS mixed with RAC at RAC/WHS ratio from 1:3 to 4:1 in (a) water and (b) 1% Triton X-100 (solid) and 1% acetone (vacant).

The efficiency increased in order of 1% Triton X-100 > 1% acetone > water. The ratio of RAC/WHS was incremented to evaluate RAC dose-dechlorination response. The efficiency increased with increasing RAC dose. In case of RAC/WHS ratio at 4 under 1% Triton X-100, approximately 24% of chlorines of the PCBs in WHS were removed after 100 d.

Significance

Remediation of soil and sediments contaminated with PCBs remains a scientific and technical challenge. In order to overcome the short-comings of current remediation strategies for contaminated sediments, our effort has been given to the development of RAC strategy. Trinity River Sediment and Waukegan Harbor Sediment contaminated with PCBs were effectively treated on RAC impregnated with palladized iron particles. During the treatment, we proved that the electrochemical dechlorination of PCBs and the physical adsorption and sequestration of PCBs and their reaction intermediates can be simultaneously achieved with the hybrid RAC composite. Based on the results, the concept of a "reactive" cap/barrier composed of RAC pellets contained between thin geo-textile membranes can be proposed. We envision that the concept of RAC cap/barrier will be an effective option for the environmental risk management of PCBs-contaminated sites. Results from this study will therefore be of interest to chemists and engineers working for remediating environmentally contaminated sites with PCBs or other chlorinated compounds.

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Information Transfer Program Introduction

In 2011, the Texas Water Resources Institute continued its outstanding communication efforts to produce university-based water resources research and education outreach programs in Texas.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2011TX401B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	17
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	
Principal Investigators:	Neal Wilkins, Danielle Kalisek, Leslie H Lee, Courtney Smith, Jaclyn Tech, Kevin Wagner, Ralph Wurbs, Kathy Wythe

Publications

1. Arnold, J. G., J. R. Kiniry, R. Srinivasan, J. R. Williams, E. B. Haney, and S. L. Neitsch, 2011, Soil and Water Assessment Tool Input/Output File Documentation (TR-365), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 662 pages.
2. Berthold, T. Allen, 2011, Public Service Announcements for the Arroyo Colorado Watershed (TR-396), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 14 pages.
3. Berthold, T. Allen, 2011, Pesticide Education in the Coastal Zone of the Arroyo Colorado Watershed Final Report (TR-397), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 41 pages.
4. Berthold, T. Allen, 2011, North Central Texas Water Quality Final Report (TR-409), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 167 pages.
5. Berthold, T. Allen, and Jaime Flores, 2011, Arroyo Colorado Watershed Protection Plan Implementation Project Final Report (TR-411), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 43 pages.
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8. Bonaiti, Gabriele, and Guy Fipps, 2012, Evaluation of the CRITERIA Irrigation Scheme Soil Water Balance Model in Texas – Initial Results (TR-418), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 38 pages.
9. Bonaiti, Gabriele, and Guy Fipps, 2012, Methodologies for Analyzing Impact of Urbanization on Irrigation Districts (TR-419), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 33 pages.
10. Falkner, Brock, and Guy Fipps, 2011, Farm Turnout Flow Recommendations for New Outlets in Cameron County Irrigation District No. 2 (TR-377), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 17 pages.
11. Flahive, David, and Guy Fipps, 2011, Irrigation District Database Analysis Cameron County

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16. Kalisek, Danielle, B. L. Harris, Craig Runyan, and Leeann DeMouche, 2011, Efficient Irrigation for Water Conservation in the Rio Grande Basin 2010/2011 Progress and Accomplishments (TR-400), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 93 pages.
17. Lee, Taesoo, Balaji Narasimhan, and Raghavan Srinivasan, 2011, Eagle Mountain Watershed: Calibration, Validation, and Best Management (TR-408), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 50 pages.
18. Leigh Eric, and Guy Fipps, 2011, Measured Seepage of the Main Canal of Brownsville Irrigation District (TR-372), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 13 pages.
19. Leigh, Eric, and Guy Fipps, 2011, Measured Seepage Losses of Canal 6.0: La Feria Irrigation District Cameron County No. 3 (TR-373), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 19 pages.
20. Leigh, Eric, and Guy Fipps, 2011, Measured Water Losses of Lateral A in Hidalgo County Irrigation District No. 2 (TR-374), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 23 pages.
21. Leigh, Eric, and Guy Fipps, 2011, Seepage Loss Test Results in Cameron County Irrigation District No. 2 (TR-375), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 20 pages.
22. Leigh, Eric, and Guy Fipps, 2011, Flow Measurement for Rehabilitation Planning Report for Cameron County Irrigation District No. 2 (TR-376), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 18 pages.
23. Leigh, Eric, Milton Henry, and Guy Fipps, 2011, Flow Measurement for Structure Assessment in Richmond Irrigation District (TR-379), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 9 pages.
24. Lesikar, B., J. Mechell, B. Clayton, R. Gerlich, D. Kalisek, and B. L. Harris. 2011, Provide Assistance to Improve Water Quality in Hood County Final Report (TR-404), Texas Water Resources Institute, Texas A&M System, College Station, Texas.
25. Miyamoto, S., 2012, Site Suitability Assessment for Irrigating Urban Landscapes with Water of Elevated Salinity in the Southwest: Consolidated Final Report: Part 1: Water Quality and Plant Tolerance (TR-416), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 167 pages.
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System, College Station, Texas, 68 pages.
28. Swanson, Charles, and Guy Fipps, 2011, Evaluation of Smart Irrigation Controllers: Year 2010 Results (TR-401), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 36 pages.
29. Wagner, Kevin, and Larry Redmon, 2011, Lone Star Healthy Streams Final Report (TR-410), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 168 pages.
30. Waidler, David, Mike White, Evelyn Steglich, Susan Wang, Jimmy Williams, C. A. Jones, and R. Srinivasan, 2011, Conservation Practice Modeling Guide for SWAT and APEX (TR-399), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 71 pages.
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32. Di Giovanni, G., L. Lee, and B. VanDelist, 2012, Bacterial Source Tracking: Learn Why Bacterial Source Tracking is the Foremost Tool for Identifying Sources of Fecal Pollution (EM-111), Texas Water Resources Institute, Texas A&M University System, College Station, Texas.
33. Fromme, Dan D., Tom Isakeit, and Larry Falconer, 2011, Soybean Production in the Rio Grande Valley (EM-108), Texas Water Resources Institute, Texas A&M University System, College Station, Texas.
34. Gregory, L, and M. Masser, 2011, The Pond Destroyers: Common and Giant Salvinia (EM-109), Texas Water Resources Institute, Texas A&M University System, College Station, Texas.

Texas Water Resources Institute
Information Transfer Activities
March 1, 2011 – February 28, 2012

In 2011, the Texas Water Resources Institute continued its outstanding communication efforts to produce university-based water resources research and education outreach programs in Texas.

The Institute publishes a monthly email newsletter, a periodic email newsletter specific to the drought in Texas and an institute magazine published three times a year. The Institute also publishes an online peer-reviewed journal in conjunction with a nonprofit organization and uses social media to publicize information.

New Waves, an email newsletter, published timely information about water resources news, results of projects and programs, and new water-related research projects, publications and faculty at Texas universities. In January 2012, *New Waves* was converted to *Conservation Matters* to reflect its broader focus to include natural resources news and issues. As of February 28, 2012, the newsletter has a subscription of 2,269.

With Texas experiencing a record-breaking drought, the need to communicate information about the drought was realized by the Texas Water Resources Institute. Since August 2011, TWRI's communications team has published a new email newsletter dedicated to drought issues, *Drought in Texas*. The newsletter has covered such topics as predicted water policy changes because of the drought to interviews with the Texas state climatologist to reprints of AgriLife Extension articles on coping with the drought. As of February 28, 2012, *Drought in Texas* has about 2,500 subscribers.

txH_2O, a 30-page glossy magazine, is published three times a year and contains in-depth articles that spotlight major water resources issues in Texas, ranging from agricultural nonpoint source pollution to landscaping for water conservation. Subscribers are at 2,485 and approximately 1,000 more magazines are distributed.

The Texas Water Journal is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management and policy issues from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. The journal has published two issues. It currently has 205 enrolled users, although registration is not required to view the journal.

The Institute has a Twitter account to promote the institute and water resources news and education throughout the state. The Institute currently has 411 Twitter followers and engagement levels have steadily increased. It also has a project-specific blog and two project-specific Facebook pages.

Working to reach the public and expand its audience, the Institute generates news releases and cooperates with Texas A&M AgriLife Communications writers for them to produce news releases about projects as well. The Institute prepared numerous informational packets for meetings. TWRI projects or participating researcher efforts had at least 150 mentions in the media.

For each of the institute's projects, TWRI published a one-page fact sheet that explains the purpose, background, objectives, and, if applicable, accomplishments of the program.

In cooperation with research scientists and Extension education professionals, the institute published 32 technical reports and four educational materials publications, which provide in-depth details of water resource issues from various locations within the state.

TWRI continues to enhance its web presence by posting new project-specific Web sites and continually updating the information contained within the websites. The institute currently maintains 36 websites.

TWRI Program Sites:

Arroyo Colorado	arroyocolorado.org
Attoyac Bayou Watershed Protection Plan Development	attoyac.tamu.edu
Bacteria Fate and Transport	bft.tamu.edu
Big Cypress Creek Modeling and BST	bcc.tamu.edu
Buck Creek Watershed Protection Plan Development	buckcreek.tamu.edu
Caddo Lake Data	caddolakedata.us
Carters and Burton Creeks Water Quality	cartersandburton.tamu.edu
Center for Invasive Species Eradication	cise.tamu.edu
Consortium for Irrigation Research and Education	cire.tamu.edu
Copano Bay Water Quality Education	copanobay-wq.tamu.edu
Efficient Nitrogen Fertilization	n-fertilization.tamu.edu
Environmental Effects of In-House Windrow Composting of Poultry Litter	windrowlitter.tamu.edu
Evaluating BMPs to Reduce Poultry Odors	poultrybmps.tamu.edu
Fort Hood Range Revegetation	forthoodreveg.tamu.edu
Groundwater / Surface Water Interactions	waterinteractions.tamu.edu
Groundwater Nitrogen Source Identification and Remediation	groundwatern.tamu.edu
Lake Granbury Water Quality	lakegranbury.tamu.edu
Leon/Lampasas BST	leon-lampasasBST.tamu.edu
Little Brazos River Bacteria Assessment	lbr.tamu.edu
Lone Star Healthy Streams	lshs.tamu.edu
North Central Texas Water Quality	nctx-water.tamu.edu
Pecos River WPP Implementation Program	pecosbasin.tamu.edu
Rio Grande Basin Initiative	riogrande.tamu.edu
Rio Grande Basin Initiative Conference	riogrande-conference.tamu.edu
State BST Infrastructure Support	texasbst.tamu.edu
Texas Water Resources Institute	twri.tamu.edu
Texas Watershed Planning	watershedplanning.tamu.edu
Texas Well Owner Network	twon.tamu.edu
Water Resources Training Program	watereducation.tamu.edu

Completed Program Sites:

Dairy Compost Utilization	compost.tamu.edu
Environmental Infrastructures	bosque-river.tamu.edu
Improving Water Quality of Grazing Lands	grazinglands-wq.tamu.edu
Irrigation Training Program	irrigationtraining.tamu.edu

Other Sites:

Save Texas Water	savetexaswater.tamu.edu
Texas Water Journal	journals.tdl.org/twj
WATER Scholars Program	waterscholars.tamu.edu

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	6	0	0	8
Masters	7	11	0	0	18
Ph.D.	1	0	0	0	1
Post-Doc.	0	0	0	0	0
Total	10	17	0	0	27

Notable Awards and Achievements

Awards for 2009TX328B

- Third Place, Graduate Student Poster Competition, 2010 Beltwide Cotton Conferences, New Orleans, LA.
- Tom B. Slick Graduate Research Fellowship Award, 2011, College of Agriculture and Life Sciences, Texas A&M University, College Station, TX.

Awards for 2008TX311B

- J. Walter Porter Fellowship of the American Society of Civil Engineers, Texas Section, 2010-2011.
- Kolodzey Travel Grant, UT-Austin Dept. of Civil, Arch., and Env. Engineering, 2010.
- Thrust 2000 Graduate Fellowship in Engineering, 2007-2010.

Publications from Prior Years

1. 2009TX325B ("Biotransformation of pharmaceuticals and personal care products (PPCPs) at an effluent land application site") - Articles in Refereed Scientific Journals - Carr, D.L., A. N. Morse, J. C. Zak, and T. A. Anderson, 2011, Biological Degradation of Common Pharmaceuticals and Personal Care Products in Soils with High Water Content, Water, Air, & Soil Pollution 217(1) 127- 134, DOI: 10.1007/s11270-010-0573-z http://www.springerlink.com/content/w0k75118g9264121/fulltext.html.
2. 2009TX325B ("Biotransformation of pharmaceuticals and personal care products (PPCPs) at an effluent land application site") - Articles in Refereed Scientific Journals - Carr, D.L., A. N. Morse, J. C. Zak, and T. A. Anderson, 2011, Microbially mediated degradation of common pharmaceuticals and personal care products in soil under aerobic and anaerobic conditions, Water, Air, & Soil Pollution 216(1): 633 – 642, DOI: 10.1007/s11270-010-0558-y http://www.springerlink.com/content/873327g50736451h/fulltext.html.
3. 2009TX325B ("Biotransformation of pharmaceuticals and personal care products (PPCPs) at an effluent land application site") - Dissertations - Carr, Deborah, 2009, Biotransformation of estrogens and synthetic pharmaceuticals and personal care products in a sandy loam soil, Ph.D. Dissertation, Environmental Toxicology, Texas Tech University, Lubbock, TX, 126 pages.
4. 2009TX325B ("Biotransformation of pharmaceuticals and personal care products (PPCPs) at an effluent land application site") - Conference Proceedings - Carr, D.L., A. N. Morse, and T. A. Anderson, 2009, Biotransformation of estrogens and synthetic pharmaceuticals and personal care products in a sandy loam soil, “in” SETAC North America Annual Meeting.
5. 2008TX311B ("An Environmental Flows Information System for Texas") - Conference Proceedings - Hersh, E.S. and D.R. Maidment, 2010, An Environmental Flows Information System for Texas, “in” ASCE EWRI World Environmental and Water Resources Congress, May 2010, Providence, RI.
6. 2010TX357B ("Impact of Saline Irrigation Water on Citrus Rootstocks in the Lower Rio Grande Valley") - Other Publications - Simpson, C.R., A. Volder, S. D. Nelson, G. Schuster, J. C. Melgar, J. Jifon, and S. King, 2011, The Effects of Salinity on Citrus Rootstocks in South Texas, Texas A&M University Horticulture Graduate Council Poster Competition, College Station, TX, November 30, 2011.
7. 2010TX357B ("Impact of Saline Irrigation Water on Citrus Rootstocks in the Lower Rio Grande Valley") - Other Publications - Simpson, C.R., A. Volder, S. D. Nelson, G. Schuster, J. C. Melgar, J. Jifon, and S. King, Does Grafting Effect Salinity Tolerance? Texas A&M University-Kingsville Citrus Center Seminar Series, February 20, 2012, Invited Speaker.
8. 2010TX359B ("Anthropogenic Influence on Tetracycline Resistance in a Rapidly Urbanizing Texas Stream") - Articles in Refereed Scientific Journals - Sullivan, B. A. and R. Karthikeyan, 2011, Occurrence and prevalence of antibiotic resistant bacteria in a perennial stream, Journal of Natural and Environmental Sciences, 2(2) 25-31.
9. 2010TX359B ("Anthropogenic Influence on Tetracycline Resistance in a Rapidly Urbanizing Texas Stream") - Conference Proceedings - Sullivan, B. A. and R. Karthikeyan, 2010, Anthropogenic Influence on Tetracycline Resistance in a Subtropical Watershed, “in” ASABE 21st Century Watershed Technology: Improving Water Quality and Environment Conference, Universidad EARTH, Costa Rica.
10. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Dissertations - Wen, Yujin, 2011, Cotton Production under Traditional and Regulated Deficit Irrigation Schemes in Southwest Texas, “Ph.D. Dissertation”, Department of Soil and Crop Sciences, College of Agriculture and Life Sciences, Texas A&M University, College Station, TX, 103 Pages.
11. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Other Publications - Wen, Yujin, Diane L. Rowland, J. Tom Cothren and Giovanni Piccinni, 2011, Monitoring soil moisture: comparison between neutron probe and profiler PR2, “in” Proc. of the 2011 Beltwide Cotton Conferences, Atlanta, GA. (Poster)

12. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Conference Proceedings - Wen, Yujin, Diane L. Rowland, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Armen R. Kemanian and Ty K. Witten, 2010, Cotton production under traditional and regulated deficit irrigation schemes in Southwest Texas (final report), “in” Proc. of the 2010 ASA-CSSA-SSSA International Annual Meetings, Long Beach, CA.
13. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Conference Proceedings - Wen, Yujin, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Diane L. Rowland and Armen R. Kemanian, 2010, Regulated deficit irrigation application and the physiological responses of cotton (Gossypium hirsutum L.) in Southwest Texas (updated report), “in” Proc. of the 2010 Beltwide Cotton Conferences, New Orleans, LA.
14. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Other Publications - Wen, Yujin, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Diane L. Rowland and Armen R. Kemanian, 2010, The lint yield and fiber quality of cotton (Gossypium hirsutum L.) under several regulated deficit irrigation schemes in Southwest Texas, “in” Proc. of the 2010 Beltwide Cotton Conferences, New Orleans, LA. (Poster)
15. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Conference Proceedings - Wen, Yujin, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Diane L. Rowland and Armen R. Kemanian, 2009, Regulated deficit irrigation and cotton production responses in Southwest Texas, “in” Proc. of the 5th USCID Irrigation and Drainage International Conference, Salt Lake City, UT.
16. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Other Publications - Wen, Yujin, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Diane L. Rowland and Armen R. Kemanian, 2009, Regulated deficit irrigation application and the physiological responses of cotton (Gossypium hirsutum L.) in Southwest Texas (updated report), “in” Proc. of the 2009 ASA-CSSA-SSSA International Annual Meetings, Pittsburgh, PA. (Poster)
17. 2009TX328B ("Regulated Deficit Irrigation Application and Cotton Production in SW Texas") - Articles in Refereed Scientific Journals - Wen, Yujin, Diane L. Rowland, Giovanni Piccinni, J. Tom Cothren, Daniel I. Leskovar, Armen R. Kemanian, and Joshua D. Woodard, 2012, Lint yield, lint quality and economic returns of cotton production under traditional and regulated deficit irrigation schemes in Southwest Texas, Submitted to the Journal of Cotton Science.